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ECONOMIC EVALUATION OF WATER

P. H. McGauhey, et al

California University
Berkeley, California

November 1969

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Final Report

ECONOMIC EVALUATION OF WATER QUALITY

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FINAL REPORT

ECONOMIC EVALUATION OF WATER

to the

Federal Water Pollution Control Administration
Department of the Interior
on
FWPCA Research Grant Project 16090DLU
(WP-00597-06)

by the

University of California
Berkeley

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November 1969

Sanitary Engineering Research Laboratory
College of Engineering
and
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University of California
Berkeley

SERL Report No. 69-8

FWPCA Review Notice

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ABSTRACT

The tendency to set quality of the water resource rather than quality of discharges as the objective of environmental control makes it necessary to develop some relationship between concentration of individual pollutants in the resource and in the discharge in terms of characteristics of the receiving estuary. Moreover, the growing percentage of the water resource which is degraded in quality through beneficial use together with the increasing investment necessary to restore water quality, makes it important to minimize the cost of achieving water quality objectives. The study makes use of modern mathematical models, programming techniques, and input-output analysis to optimize quality control systems; and illustrates the use of the models by examples drawn from San Francisco Bay data and quality requirements.

This report was submitted in fulfillment of project 16090DLU (WP-00597-06) under the partial sponsorship of the Federal Water Pollution Control Administration.

PREFACE

NEED FOR STUDY

A general need for studying the economic value of water quality derives from the fact that the burgeoning population of the United States and the economic growth on which it depends for an ever-increasing standard of living requires a growing per capita utilization of water. Inasmuch as the water resource of the nation is relatively constant, this means that the consequences of beneficial use of water becomes more evident each year; and because these consequences are a decrease in water quality which can be offset only by investment in expensive water purification works, the economic aspects cannot be ignored.

The specific need for study, however, derives from the general need in a variety of ways. In the practical sense "quality" has no absolute definition but is measurable only in terms of the use water is expected to serve. Consider as an extreme example 10,000 acre-feet of snow melt on the one hand and an equal amount of sea water on the other. Presumably any citizen would consider the fresh water as being of vastly higher quality than the sea water. Yet either might serve such purposes as navigation or industrial cooling water equally well. The untreated sea water would, of course, be useless for domestic supply, agriculture, and industrial process water, whereas the fresh water might be catastrophic to aquatic life if discharged suddenly into a saline estuary. To overcome either of such extremes requires an economic investment in water quality management. Considering that ranges of quality rather than absolute levels characterize the acceptability of water in any beneficial use, it is at once evident that some spectrum of water quality criteria can be arbitrarily set up to define decreasing degrees of acceptability of water, ranging from the highest aesthetic level to complete disaster. The problem then becomes that of determining the economic value to the user of having available water at one level of quality as against some other level, quality being defined in terms of those characteristics of water of importance to the specific use concerned. Thus the first specific need for study of the economic value of water quality is to determine some means by which to calculate, or at least to estimate, the value to the user of any specific quality of water in terms of comparative economic return to him in his enterprise.

A second need for studies leading to methods for evaluating water quality economically lies in the area of achievement of public policy. To an increasing degree citizens and public officials are of the mind that high-quality environment, pure water, and clean air are the heritages of all Americans and constitute the objectives of public policy aimed at environmental control. At the same time, unregulated population growth has persisted and society is insisting that each individual in that population be enabled to enjoy a standard of living which only further exploitation of resources will make possible. To the extent that depreciation of water quality is a by-product of economic growth, the disparity between national objectives and the harsh realities of resource exploitation presents several economic questions:

1. How great is the public investment needed to achieve our national environmental goals of water quality?
2. How far can we in reality progress toward these national goals of water quality with that fraction of our national wealth we feel justified in dedicating to water resource management, considering other demands for investment on a necessarily finite national budget?

3. What is the optimum way to invest available funds in water quality management in order to enhance economic growth while at the same time achieving water quality goals?

4. How can the water quality criteria established by regulatory agencies for any given sector of the water resource be achieved at a minimum cost to the water-using sector of the economy?

The foregoing questions generate yet a third need for studies such as herein reported. This is for ways to adapt modern methods of mathematical modeling, systems analysis, and operations research to the economic evaluation of water quality. The questions involved are complex in the extreme; numerous alternative decisions are possible; and optimum economic solutions are required. Thus the third need in a logical sequence becomes the first need in research, i.e., the development of mathematical approaches. Thereafter, the way to their application to practical problems can be sought.

NATURE OF STUDY AND REPORT

The studies herein reported were undertaken in response to the need outlined in the preceding paragraphs. The report itself is composed of two major sections. In the first is summarized, in limited detail, work completed during the period September 1962 to January 1969 and reported in four widely distributed reports [1-4] to the sponsoring agencies, which included: Resources for the Future, National Institutes of Health, and the Federal Water Pollution Control Administration. The first section of the report covers primarily those phases of the study in which mathematical modeling and systems analysis were developed and tested for applicability to specific problems outlined in the 'Need For Study.' Four phases of the study are reported in Section I. They include:

1. An engineering economic model for water quality management;

2. A mathematical model of dissolved oxygen concentrations in fresh water streams;

3. A linear programming water quality control model; and

4. A multicomponent model of optimal quality control in estuarine waters.

The first two of these four phases were, as hereinafter noted, concerned with maintenance of the quality of water in flowing streams; the second two with the quality of estuarine waters.

The fifth phase of the study, which is the subject of the second section of this report, concerns the application of the previous estuarine models to a real situation – the San Francisco Bay – for which results of several years of study by other investigations, costing several millions of dollars, made specific data available. In addition, advantage is taken in this section of an input-output model of the economy of the San Francisco Bay area, likewise developed at considerable cost in time and money to other projects and agencies. From it is evaluated the constraint of waste water quality maintenance costs imposed on the economic growth which might otherwise be expected to accrue from an optimum allocation of scarce water to various beneficial uses. Inasmuch as the material in Section II of this report has not previously been evaluated in the context of water quality, it is developed in detail under the more appropriate heading, 'A Multisectoral Programming Analysis of the Waste Water Economy of the San Francisco Bay Region.'

Objectives, concepts and rationale, general methodology, and major conclusions are discussed later as they pertain to the various phases of the study.

The report, then, is the result of the cooperative effort of a number of individuals representing several disciplines.

ORGANIZATION FOR STUDY

The study was begun in 1962 through a one-year predoctoral fellowship grant to Mr. Richard Frankel from Resources for the Future, Inc. Early results indicated that the subject of economic evaluation of water quality might be worth further exploration. For that purpose NIH Grant No. WP-00597 was made in 1963 to Professors P. H. McGauhey and Walter F. Rowland; and later to P. H. McGauhey and Dr. G. T. Orlob of the Sanitary Engineering Research Laboratory of the University of California at Berkeley. Under the guidance of these faculty investigators and the Department of Natural Resources Economics of the University, Mr. Richard Frankel completed the first phase of the study and developed the report [1] as his dissertation for the Ph.D. dgree in Water Resources Engineering. Dr. Richard Frankel and Mr. William W. Hansen, an advanced graduate student in Water Resources Engineering, reported [2] phase 2 of the study.

The third phase of the study was conducted under Grant No. USDI WP-597 as responsibility for the Water Pollution Control Program was transferred from the Department of Health, Education, and Welfare to the USDI Federal Water Pollution Control Administration. Mr. John P. Carew, an economist, joined the project staff in 1965. With professional guidance in the field of economics from Professor B. N. Ward of the University of California Department of Economics, and in the field of operations research and systems analysis from Professor R. M. Van Slyke, also of the University of California staff, the study produced a third report [3] under the authorship of Mr. Carew and Professor McGauhey. Ultimately this report was expanded by Mr. Carew independently to satisfy the thesis requirements for his Ph.D. in Economics.

Under a continuation of the USDI WP-597 Grant and with the continued cooperation of Professor Van Slyke, the work of Dr. Carew was developed to a much more sophisticated degree by Mr. Shishir K. Mukherjee. His report on the fourth phase of the study [4] served both as the basis for his doctoral degree in Operations Research Engineering and as one of the models needed for the fifth and final phase of the study.

To continue the study from the Mukherjee report [4] and to produce the added material needed for the final report, use was made of both the mathematical models previously developed and of competence gained in input-output studies by Dr. H. Craig Davis, Dr. E. M. Lofting, and Mr. Jona Bargur during professional as well as doctoral studies in the fields of Economics and Water Resources Engineering, under grants to Professor P. H. McGauhey from the University of California Water Resources Center, the OWRR, the Bureau of Mines, the Corps of Engineers, and the California State Department of Water Resources. Section II of the report, which constitutes phase 5 of the study, is authored by Mr. J. S. Bargur, Dr. E. M. Lofting, and Dr. H. Craig Davis.

Upon the retirement of Professor P. H. McGauhey from the University of California, Dr. E. J. Middlebrooks was appointed by the University to serve as Faculty Investigator for the remaining months of the contract, although emergency arrangements were made with Professor McGauhey to participate in producing the final report.

ACKNOWLEDGMENTS

The faculty investigators and project staff who served during the more than six years the study was in progress are indebted to so many individuals for guidance, counsel, programming, and technical assistance that almost no listing can be complete. Attention has already been called, in the section 'Organization For Study,' to many whose assistance made it possible for the designated Faculty Investigators in engineering to continue with studies involving economics and systems. Others who might be singled out for special thanks include Professors S. V. Wantrup, M. F. Brewer, D. I. Jenkins, Ray B. Krone, David K. Todd, William F. Jewell, Roger K. Glassey, and Robert E. Selleck of the University of California; and Professor Clarence J. Velz of the University of Michigan; Mr. A. R. Blanch and Mr. William Pierce of the Federal

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SECTION I

Summary of Phases 1-4

by

P. H. McGauhey

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I. SUMMARY OF PHASE 1

INTRODUCTION

The initial phase of the study was published in January 1965 as SERL Report No. 65-3 of the University of California [1]. It was authored by Mr. Richard J. Frankel and entitled "Economic Evaluation of Water Quality; An Engineering-Economic Model for Water Quality Management; First Annual Report."

CONCEPT AND RATIONALE

The study was based on the concept that the water quality requirements established for a given stream system by a regulatory agency might be met more economically by engineered systems designed to accomplish a different spectrum of objectives than is commonly the case. To test this hypothesis a computer model was established to simulate a water course of specified characteristics and subject to flow regulation at its headquarters. Within the upstream area, a community of specified size was presumed to discharge domestic sewage effluent into the stream. Downstream a second community, also of specified size, was presumed to draw upon the stream for its domestic water supply. The reach of stream between the effluent outfall and the water supply intake was of specified length, subject to natural self-purification, and under the jurisdiction of a regulatory agency empowered to impose quality standards deemed appropriate to the protection of beneficial uses it might deem important. No augmentation of the stream by influent springs or by tributaries was assumed. This, however, was merely to simplify the model for the initial study, as there is nothing in the concept to preclude such additions in any amounts or of any quality characteristics.

The principal factors in the system which were subject to natural or artificial variation included:

1. Discharge or flow of stream.
2. Quality of water in stream above sewer outfall.
3. Degree of self-purification of stream.
4. Degree of treatment of waste water.
5. Concentration and pollutant content of waste water.
6. Nature of beneficial use of the stream.
7. Water quality standards imposed on stream.
8. Degree of treatment of water supply of downstream community.
9. Division of treatment between the two communities.

OBJECTIVES OF STUDY

The specific objective of the study was to utilize computer techniques to determine the effects of the seven variables on the cost of water reuse. That is, to determine how by process engineering the quality of water required in the stream and by the domestic water supply could be achieved at a minimum cost. Conceivably it might be cheaper in terms of public investment to vary from conventional treatment

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of sewage and water supply, take advantage of the self-purifying ability of the stream, and so operate the system as to achieve all water quality objectives at a reduced cost.

PROCEDURE

The study gave first consideration to factors which influence pollution-cost relationships, including:

1. Quality factors in domestic waste water which affect water purification plant operation.
2. Cost and removal efficiencies of waste water treatment plants.
3. Cost of water treatment plants and processes.
4. Stream flow in its relation to water quality.

More than 30 pages of the report [1] is devoted to factors in cost-quality relationships, with particular concern for:

1. Suspended solids and dissolved organic matter.
2. Coliform organisms (bacterial indicator of sewage pollution).
3. Nutrients such as nitrogen and phosphates.
4. Surface active agents.*

Having established the basic cost functions needed in the economic analysis, the study then turned to the development of computer models and an explanation of the methodology involved. The following models were established for computer programming:

1. A dynamic oxygen sag model, incorporating photosynthetic effects.
2. A biological purification (bacterial die-away) model.
3. A detergent degradation model.

The models were then programmed for the IBM 1620, the coliform die-away being set up for both chlorinated and unchlorinated effluents for numerous travel times downstream under varying conditions. Computer programs are included in the report [1].

Analyses were made both on the basis of laboratory studies, which became a limited aspect of the project, and on actual reported costs and stream standards.

CONCLUSIONS

Phase 1 of the study reported some 21 conclusions drawn from results of computer analysis of the engineering-economic model developed in the study. Typical of the most important of these, in terms of the concepts on which the study was postulated, is that: The amount of savings to water purification plants downstream is a direct benefit of improved upstream treatment. The ratio of cost savings downstream to the costs of additional treatment upstream is quite small, varying from 0 to 0.10. Maximum return per dollar investment is realized when secondary treatment is added to primary.

---

*During the period of phase 1 of the study (1962-1964), detergents were considered a problem in water quality. The changeover to biodegradable detergents occurred in June 1965.

The model itself represents a successful tool, capable of further development and extension, to evaluate the effects of pollutional loads and water quality management techniques on downstream beneficial uses. Implicit in the conclusions reported, although not spelled out in detail, is the idea that the model might be most useful when extended to more complex systems, possibly regional in nature. In the simple situation the problem of optimizing treatment costs by allocating certain treatment functions to waste water, water purification, and natural processes is complicated by the nature of treatment processes themselves. Specifically, treatment processes represent large discrete variables, only a few of which comprise a treatment plant. For example, the engineer does not design a waste water sedimentation tank to remove 5, 10, 15, 20, etc. percent of the suspended solids. Either none at all are removed or 50 to 60 percent are taken out. Thus the variability which might be shown up by the model is obscured by the size of increments involved. Moreover, even if percentage removals were highly variable, it seems unlikely that costs would follow the same sensitivity scale. Certainly the cost ratio of providing sedimentation, for instance, to remove 5 percent instead of 10 percent of solids is by no means 1:2.

Nevertheless the study did report important conclusions and present discussions of their subtleties too extensive to summarize here.

II. SUMMARY OF PHASE 2

INTRODUCTION

Phase 2 of the study was both an outgrowth of, and a refinement of, phase 1. Its results were published in August 1965 as SERL Report No. 65-11. As noted in a previous section of this report, Mr. William W. Hansen joined with Dr. Richard J. Frankel in authoring it. It represented the Second Annual Report of the project on Economic Evaluation of Water Quality and was subtitled "A Mathematical Model of Dissolved Oxygen Concentration in Freshwater Streams."

CONCEPT AND RATIONALE

By far the most common criterion of water quality which has historically been applied to flowing streams is its oxygen resource in terms of dissolved oxygen (DO). Reduction in BOD has therefore long been the principal objective of biological treatment of waste water as well as the parameter by which the effectiveness of treatment has been judged. Since Ellis [5] first observed in 1937 that 5 mg/ℓ of DO is needed to support a good mixed fish faunae, the tendency has grown to establish an average DO content of 5 or 6 mg/ℓ as the standard to be met in water quality management. During the investigative work which led to the oxygen sag model established for phase 1 of the study, evidence was found which indicated that the diurnal variation in DO content and the rate of change of oxygen tension may not be held below their critical limits for aquatic life by the simple imposition of a standard criterion of 5 mg/ℓ average DO. Should such prove to be the case, economic conclusions based upon the engineering-economic model of phase 1 might become unacceptable. Pursuant to this rationale, phase 2 was initiated for the following purposes.

OBJECTIVES OF STUDY

Three objectives were established for phase 2 of the study:

1. To set up a mathematical model expressing the relationships between oxygen-demanding fractions of a waste water and the responses of a living stream.
2. To apply computer techniques to the model to determine the magnitude and location of maxima and minima in the oxygen resources of the stream.
3. To verify the mathematical model by applying it to data observed in the field.

PROCEDURE

Pursuant to the foregoing objectives a new oxygen sag model was developed to include oxygen consumption by anaerobic decomposition products of the benthos and decay of the initial oxygen saturation deficit, as well as the oxygen consumed in biodegradation of suspended and dissolved organic matter and the consumption of oxygen by photosynthesis. This model was programmed for the computer as reported in the Second Annual Report [2].

To test the program it was applied to a case study utilizing data for the Flint River published by the Water Resources Commission of the State of Michigan. Their data permitted description of the diurnal variation in DO at a number of points along a critical reach of stream.

RESULTS AND CONCLUSIONS

Although certain adjustments and assumptions were made necessary by some conditions peculiar to the Flint River situation, the conditions existing in the stream were found to be describable by the theoretical model. It was therefore concluded that the model could be used advantageously to determine what improvements in the stream environment would result from greater dilution, and from various changes in plant operating or streamflow management practices.

III. SUMMARY OF PHASE 3

INTRODUCTION

By the time phase 2 of the project had been completed, a number of changes in the public attitude toward resource conservation were emerging. Most significant of these were an emphasis on quality "of the environment" and, in the case of water, "quality of the resource itself" in contrast with a previous preoccupation with "pollution" in terms of the quality of individual waste discharges. This meant that quality objectives were to be set for bodies of water by regulatory agencies and, although these objectives might be met only by regulating the quality of individual waste discharges, there was no reason to believe that the most economical way to achieve these objectives was by subjecting each waste discharger to exactly the same discharge requirements.

From the viewpoint of the project this change in public objectives now offered two possible directions of investigation. The model developed in phases 1 and 2 of the study might be expanded, or emphasis placed on the most economical way to achieve any given water resource quality objectives. It was decided to adopt the second alternative for a number of reasons:

1. Phases 1 and 2 of the study had already demonstrated that the model could be extended to more complex systems where investment decisions must be made. However, its resolving power was best suited to such complex systems involving multiple installations and regional water quality considerations rather than to a simple situation where water treatment alternatives would approach a situation of indivisibility.
2. To expand the model to optimum proportions would mean a research commitment at a greater than authorized budgetary level and probably on a long-term basis because considerable time might be expected to elapse between the present and the future date when water quality management might indeed be practiced on a regional scale suited to the model.
3. It seemed evident that the newer "resource quality" approach was the one most certain to dominate public policy in the years ahead and that, therefore, directing attention to its implications should be the most productive of research results.
4. Data suited to the needs of the project were available as a result of extensive studies of the San Francisco Bay System by other investigators.
5. No change in the needs and objectives for which the research grant was made was involved in the shift of emphasis.

CONCEPT AND RATIONALE

The concepts and rationale underlying phase 3 of the study are essentially presented in the preceding paragraphs. Specifically, it was postulated that by modern methods of systems analysis and programming techniques it should be possible to determine the economic effects of changing the quality requirements of a water resource in terms of the minimum cost of waste water management to any specific community.

OBJECTIVES OF THE STUDY

The specific objective, as set forth by Dr. John Carew and Professor P. H. McGauhey in the report on phase 3 [3] of the study was to develop a linear programming water quality control model capable of minimizing the cost of achieving any given water quality goal when the concentrations of various waste products were reduced to imposed, or required, levels by presently-known technology.

PROCEDURE

The procedure utilized was to construct a mathematical linear programming water quality control model and then to illustrate its use by applying it to data available from local sources. First it was assumed for purposes of the study that the quality of water in the basin to be analyzed was characterized by some 23 chemical components which are released into the San Francisco Bay by three municipalities and nine individual industries. However, for purposes of illustrating the use of the model, only the eleven characteristics for which data were most complete were utilized.

From data available from literature cited in the report [3], the cost in dollars per million gallons of water treated to each of the following six levels was obtained for 17 common pollutants, including the eleven utilized:

0. No treatment.

1. Conventional primary treatment.

2. Conventional secondary treatment.

3. Coagulation with lime or alum, sedimentation, and rapid sand filtration.

4. Sorption.

5. Electrodialysis.

6. Evaporation.

Capital costs of treatment systems were handled outside the model for reasons of convenience.

For purposes of illustration it was assumed that all 12 dischargers were presently required to treat wastes at primary level, although the model itself could handle any combination of required treatments had data on this aspect been available.

The model was used to determine what degree of treatment might be imposed on each of the 12 dischargers if the objective was to reduce to concentration limits (set by the local Water Quality Control Board) pollutants reported as entering the Suisun Bay – Lower San Joaquin River [6], including:

1. Phenol

2. Chlorides

3. Nitrogen

4. Phosphate

5. Dissolved silica

6. Total sulfide

7. Total suspended solids
8. Oil and grease
9. COD
10. BOD
11. Flow volume.

RESULTS AND CONCLUSIONS

Although the solutions presented in the report [3] for purpose of illustration depend upon inputs of somewhat restricted data, it is evident that substantial savings to the 12 dischargers as a whole would result if a nonuniform spectrum of requirements was imposed. That is, one particular discharger of a given pollutant might not be required to treat his wastes, whereas another discharger of the same material might have to treat to the third or fourth of the six levels noted. It was also evident from the results that the linear programming model could readily be applied to wastes restricted to different standards for different quality factors (pollutants). It could be adapted to partial flows as well, should industry choose to split its waste streams and apply different degrees of treatment to different fractions of its discharge.

IV. SUMMARY OF PHASE 4

INTRODUCTION

One of the major limitations of the Linear Programming Water Quality Control Model reported in phase 3 [3] is that the quality standards utilized in the solution are expressed as the maximum allowable quantities of each waste constituent discharged to the estuary. Although this is in part due to the custom of setting discharge standards prevailing at the time, it does not readily get at maximum allowable concentration levels in the water resource itself. This limitation could become increasingly significant because the tendency to place restrictions on water resource quality was accompanied by a growing concern for ecosystems of estuarine waters. Specifically, it was questioned that although the receiving water might meet requirements once waste constituents were well dispersed, what would be the situation in water masses during the interval between discharge and equilibrium dispersal?

Phase 4 was initiated in an effort to refine phase 3 by the development of dispersion models for optimum allocation of water quality and the integration of such dispersion models with the water quality control model of phase 3. Dr. Shishir K. Mukherjee conducted this phase of the study and prepared the report [4].

CONCEPT AND RATIONALE

As in phase 3, the underlying rationale of phase 4 was that:

1. Although economic grounds alone are not a sufficient basis for water quality control, the objectives of control should be attained at a minimum cost.

2. Operations research and systems analysis techniques can be applied to optimizing the cost of achieving water quality objectives.

3. By internalizing various technological external diseconomies, water quality objectives can be dealt with to a satisfactory degree; i.e., the dilemma of environmental degradation as the price of economic prosperity can be resolved.

OBJECTIVES OF THE STUDY

Five specific objectives were listed in the report on phase 4 [4]. They included:

1. To study the transportation, dispersion, and degradation of wastes constituents in an estuarine basin — aimed at relating the resulting concentration to the amounts and locations of waste discharges and hydrological parameters.

2. To develop dispersion models of optimal allocation of water quality in an estuary to achieve various related objectives, and solution of the continuous versions of these models by the application of optimal control theory to obtain an insight into the nature of optimal discharge policies.

3. To develop discrete versions of the dispersion models as linear programs, with a view to using the discrete data available from sampling studies in an estuary.

4. To develop an integrated multicomponent model of dispersion and waste treatment which will simultaneously provide an optimal plan of waste treatment, along with a plan of optimal waste discharge along the estuary, given a prescribed quality standard, and solve it as a linear program.

5. To study various modifications of the model and the economic effects of various alternative quality-improvement projects such as flow augmentation and transportation of waste by piping within the estuary or directly into the ocean.

PROCEDURE

The procedure was to develop an optimization model based on a one-dimensional description of the dispersion process which includes both longitudinal dispersion and advection. Although the final model was developed with reference to an estuary, it is regional in nature and applicable to a river basin terminating in an estuary. A steady state model was likewise described in detail for quality conditions averaged over a tidal cycle. To include seasonal variations in volume of flow, waste generation and discharge rates, and other hydrological parameters, an unsteady state model was also developed.

A duality theory for a continuous mathematical programming problem was formulated, as was a linear optimal control theory and a continuous dispersion model. After rigorous proving of these theories by mathematical methods, the dispersion model was formulated for mathematical programming and a series of problems examined. Thereafter a waste treatment model was developed. It generated an optimal waste treatment plan for all waste-producing agencies in the region by minimizing the total waste-treatment costs. Finally a complete model of estuarine water quality management was developed by a synthesis of the dispersion and waste treatment models. Economic interpretations of the synthesized model are discussed and the model illustrated by an example from the San Francisco Bay system.

RESULTS AND CONCLUSIONS

The principal conclusions drawn by the author of the report on phase 4 [4] are:

1. The boundaries of knowledge about water pollution, waste treatment, and mixing processes in estuaries are sufficiently limited that much is to be desired in terms of understanding of these processes before they can be described in precise mathematical terms.

2. No reliable theoretical method is available for most estuarine situations. Additional research is needed to develop a three-dimensional description of the dispersion process along with a method of estimating directional dispersion coefficients.

3. Movement and resulting concentrations of conservative substances can be described adequately if a proper description of the dispersive and advective processes is available. However, for nonconservative constituents the accuracy of a model is dependent to a great extent on the reliability of the estimates of the reaction rate constants. Usually these estimates are arrived at by subjective judgments based on the experience of the investigator with the particular environment and waste discharges. There is a need to seek better mathematical descriptions of nonconservative processes, particularly of the biological reactions.

4. A need for continual search for more efficient, complete, and inexpensive treatment processes cannot be overemphasized. The

optimal operation and control of treatment processes is by itself a challenging field.

5. The solutions of the water quality control model proposed is sensitive to the water quality standards used. Multicomponent water quality standards are still not available for many estuarine basins. The harmful effects of many constituents by themselves or in conjunction with other constituents on human health and marine ecology are not yet completely understood in quantitative terms. Further research and legislation are needed for establishing proper water quality standards.

6. Quantitative information regarding harmful effects and social costs of pollution and benefits from quality improvement projects are lacking today so that these costs and benefits cannot be included in optimization models. The author has developed deterministic models and considered concentrations averaged over one or more complete tidal cycles. In unsteady state models, only long-term or seasonal variations were considered. Stochastic models may be developed to study variations of water quality during a tidal cycle and effects of random variations of volume of flow in the estuary. There has been some progress in this direction.

7. Finally there is a need to consider environmental pollution as an integral problem, whether it is in the water, in the air, or in the form of solid wastes. Public awareness and public education about the desirability of a congenial environment may be a necessary step toward creating a better world for all of us.

SECTION II

Phase 5

A MULTISECTORAL PROGRAMMING ANALYSIS FOR THE MANAGEMENT OF THE WASTE WATER ECONOMY OF THE SAN FRANCISCO BAY REGION

by

Jona S. Bargur
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PREFACE TO SECTION II

INTRODUCTION

Although the objectives of phase 4 of the study were not fully attainable within the period of time allotted to that phase of the investigation, the work was a major contribution and made possible the more complex phase 5, which is the subject of this section (Section II) of the report. Inasmuch as phase 5 of the study is herein reported for the first time, it is presented in considerable detail, both in its relation to the preceding phases of the investigation and to the problem of water quality management to which it pertains. Like phase 4 it deals specifically with the estuarine waters of San Francisco Bay primarily because it is in such waters that the problem of protection of ecosystems is most acute; the consequences of poor dispersion of wastes most critical; and, as a result, the task of relating water resource quality objectives to waste discharge criteria most difficult for regulating agencies.

CONCEPTS AND RATIONALE

The basic concept underlying this phase of the study is that water quality management procedures must somehow be made equal to the task of achieving national goals of environmental quality.

Surface and subsurface supplies of water are increasingly being required to meet the rapidly growing demands for domestic, industrial, agricultural, and recreational uses. While water is generally considered to be a "renewable" resource through the hydrologic cycle, the rapid depletion of many sources and severe quality degradation of others, even such large bodies as the Great Lakes and most major estuaries including San Francisco Bay, is cause for serious concern. Suddenly man begins to fear that the entire ecological balance of major geographic regions is irreversibly threatened.

Traditionally, water development, allocation, and management programs have been based on engineering feasibility considerations and anticipated local and regional demands for various uses via some form of benefit-cost analyses. The present day problems relating to increasing concentrations of population, rapidly expanding industrial and agricultural production, and the use of water bodies as sumps for the associated wastes are causing attention to be focused on more precise forms of economic and programming analyses through which the effects of alternative water use patterns, including waste water disposal, can be more clearly revealed and evaluated. Such analytical methods, if carried forward with some degree of refinement, may force a more rational use of water and permit an optimal allocation of regional resources in which a full potential for economic growth and development may be realized.

Water quality problems relating to estuarine waters have received prime attention in the United States in the past two decades. Indeed, by contrast, far in advance of the efforts now being directed toward major limnological problems, serious concern for the fate of the large East Coast estuaries such as the Delaware and Potomac was in evidence by the late fifties. A comprehensive study of the San Francisco Bay was begun in the early sixties and major policy issues for the ultimate management of the quality of the waters of the Bay-Delta system are still under consideration.

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> "In the process of setting water quality standards for interstate and coastal waters, many States further chose to adopt standards for their intrastate waters as well. Thus, it is safe to state that for the first time in history explicitly stated water quality criteria and goals are being made applicable, and enforceable at various governmental levels, to the vast majority of the Nation's waters — be these creeks, rivers, streams, lakes, Great Lakes, or estuarine and coastal waters.
>
> ".... Major sources of pollution are return flows from municipal, industrial, power, and agricultural withdrawals, and runoff and sediment from lands used for urban, mining, agricultural, logging, and other purposes.... The waste loads from municipal systems alone are expected to increase nearly four times over the next 50 years.... Even if municipal and industrial waste loads are substantially reduced through treatment, pollution problems may continue to exist in densely populated and high industrialized areas where assimilative capacity of receiving waters is exceeded.
>
> ".... The Nation's growing population will demand multipurpose water resources development which could require a high degree of structural control of river systems in many parts of the country. On the other hand, future generations should be assured of substantial areas of preserved scenic and wild rivers, wilderness, wetlands, natural estuaries, beaches, and shores and other areas of natural beauty. Often there is an interdependence between preservation and development. The benefits of development projects that change nature's patterns must be weighed against disruptions of the natural environment." [7]

An estuary is defined by Powell [8] as "that reach of a river where river water mixes with a measurably dilute sea water." The factors governing the basic water quality characteristics of a particular estuary are extremely complex and are generally governed by the physical configuration of the estuary, the inflows from the associated river system, tidal action, prevailing winds, stratification caused by temperature, salinity, or some combination of these, and ambient temperature conditions which may or may not cause seasonal overturns of the estuarine waters.

In general, the natural assimilative capacity of an estuary, i.e., the ability of the water to receive waste discharge of all types, is considerably greater than that of a fresh water body of similar magnitude. Under such circumstances an optimal solution is sought in which the assimilative capacity of the estuary is utilized to that maximum beyond which some predetermined quality standards will be violated. The general level of treatment for waste water discharges which will preserve these standards and yet still permit the assimilative capacity of the estuary to be fully utilized will be viewed as the most "economic" level of treatment. The practical problems of finding this "optimum" are difficult, but since most industrialized societies have demonstrated, and continue to demonstrate, that they wish to minimize their investment in waste treatment facilities, the solution of the problems can be viewed in this context as being a highly desirable one.

Most river waters, and particularly the waters inflowing to San Francisco Bay, contain high concentrations of nitrogen and phosphorus. These elements form the basis for the rapid development of algal blooms, and hence are called "nutrients" or biostimulants. There is some evidence to indicate that industrial and domestic sewage effluent now being discharged in large quantities into the Bay may have an inhibiting effect on the algal growth and thus if improved waste water discharge practices were implemented at the present time the rapid growth of algae would result [9].

Thus the complex and delicate balance of the water quality problem in an estuary requires a total view of the waste water discharges of the surrounding region and an understanding of the prevailing sectoral interrelationships in addition to the synergistic effects of the discharges as mixing and dispersion takes place in the estuary itself.

The problem therefore has two major aspects, first the clear analysis of the industrial structure of the surrounding region and the economic interrelationships of the major waste water generating sectors, and secondly a dispersion model for the estuary in which well-defined mixing and diffusion patterns for pollutants can be traced. Without these two key aspects of the problem being set out independently and then fused, meaningful analyses cannot be undertaken or overall treatment levels determined relative to desired quality standards.

Traditionally, in-stream water quality problems have fallen primarily into the realm of hydraulic and sanitary engineering, hence the basic research approach to problems of this type has evolved around the mixing and dispersion concept of fluid mechanics and the dissolved oxygen and BOD relationships of water and wastes. However, more recently a multidisciplinary approach to water quality problems has begun to characterize research in the water resources field.

OBJECTIVES OF STUDY

The general objective of phase 5 of the study, herein reported, was to attempt to unify the various and diverse factors bearing on estuarine water quality management into an operational analytical technique. The specific objective was to develop a water quality management model through the conjunctive use of input-output and linear programming techniques, making use of programs and concepts developed in related research on the Economic Evaluation of Water; and, additionally, making specific use of the steady state linear optimal dispersion model developed by Shishir K. Mukherjee in phase 4 of the study [4].

V. SAN FRANCISCO BAY AREA

IMPORTANT CHARACTERISTICS

Some significant characteristics of San Francisco Bay are presented here to give the study a level of self-contained continuity. Exhaustive studies of the Bay region have been carried out with specific objectives in view [10-12]. While much of the material these prior studies generated is descriptive and may have been a by-product of particular objectives, it is extremely valuable and frequently of high quality.

The main portion of the Bay, excluding the network of waterways known as the Delta, extends generally from the City of Pittsburg on the north to the City of San José on the south, a distance of approximately 85 miles. The approximate area of the Bay at mean tide is about 435 square miles. Simple division would indicate that its average width is somewhat over 5 miles. It is estimated that about 100 years ago the area of the Bay was of the order of 700 square miles, revealing the extent to which land at its perimeter has been claimed for uses relating to urban, agricultural, and industrial development [10].

The total volume of water in the Bay at mean tide is approximately 235 billion cubic feet.

> "The tidal prism, or the volume between high and low tides, is about 50 billion cubic feet or 21 percent of the average total volume of water in the Bay. Fifteen to 20 percent of this tidal prism is replaced by new ocean water during each tidal cycle. This is the principal mechanism by which pollutants are ultimately removed from the Bay." [10]

In general the Bay is quite shallow with an average water depth of about 20 feet. In such circumstances wind waves can disturb bottom sediments and increase the turbidity of the water [10].

The average annual precipitation in the San Francisco Bay region is about 19 inches. The mean annual evaporation for the same area is approximately 48 inches. This is double the annual precipitation which results in the loss of more than 650,000 acre-feet of water each year by surface evaporation alone [10].

POPULATION DISTRIBUTION AND PROJECTIONS

For purposes of this study the San Francisco Bay region has been defined as the nine counties region immediately surrounding the Bay, i.e.,

Alameda
Contra Costa
Marin
Napa
San Francisco
San Mateo
Solano
Santa Clara
Sonoma.

Since waters inflowing to the Bay also originate in, or flow through, Yolo, San Joaquin, and Sacramento counties it might be suggested that the term twelve-county region could more properly have been chosen. This aspect was considered,

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but since the main focus of the study is on direct waste water discharges from the region immediately surrounding the Bay, the nine counties listed above were chosen as being the representative group of counties in which the wastes associated with productive activity and population would interact directly with the waters of San Francisco Bay.

To some considerable extent population concentrations and the level of productive activities bear a high correlation in industrialized societies. Tourism, recreation, or raw materials extraction might provide exceptions to the generalization in some regions. For the Bay region, population and productivity are indeed highly interrelated. Realizing the relationship, population figures and projections (presented in Table I) can provide an insight into the magnitude of the environmental problems that will confront the region.

TABLE I

POPULATION OF BAY REGION COUNTIES 1960–1966[a]
AND ESTIMATED PERCENTAGE CHANGE 1965–2020

Counties	1960	1966	Estimated Growth 1965–2020[b] % Change
Alameda	908,209	1,045,600	111
Contra Costa	409,030	528,400	169
Marin	146,820	195,600	194
Napa	65,890	76,300	183
San Francisco	740,316	738,100	36
San Mateo	444,387	538,900	58
Solano	134,597	162,700	588
Santa Clara	642,315	924,500	122
Sonoma	147,375	183,000	409
Total	3,638,939	4,393,100	
Percent Increase		20.7%	

[a] See Reference [13], Table B-7.

[b] See Reference [11], Table 1.

Total regional population figures and projections are shown in Table II on the following page.

TABLE II

POPULATION PROJECTION IN 9-COUNTY
SAN FRANCISCO BAY REGION
1965-2020

	Year						
	1965	1970	1975	1980	1990	2000	2020
Population (10^3)	4,336[a]	4,943[b]	5,550[b]	6,158[a]	7,471[b]	8,785[a]	10,800[a]

[a] See Reference [11].

[b] Interpolated.

GENERAL ECONOMIC CHARACTERISTICS

In 1963 the State of California accounted for 11.7 percent of U. S. Gross National Product [14,15]. Of actual dollar value ($65.3 billion) the nine-county Bay region produced approximately 17 billion dollars* or about 25 percent of total state product. A comparison of the relative sources of civilian income from participation in current production for California and the United States shows that for practically all major categories California proportions vary only slightly from those of the U. S. [16]. For 82 major categories of productive activity [17] California lacked a Coal Mining sector and the Bay region additionally lacked the following sectors: Chemical and Fertilizer Mineral Mining, Iron and Ferroalloy Ores Mining, Nonferrous Metal Ores Mining, Tobacco Manufactures, Wooden Containers, and Engines and Turbines. All other categories of productive activities were present in their various forms.

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*See Table IV, this report.

VI. THE NINE-COUNTY BAY AREA MULTISECTOR
MODEL FOR 1963

GENERAL DESCRIPTION OF AN INPUT-OUTPUT MODEL

Input-output analysis is an econometric technique which focuses upon the interdependencies among the various industries or sectors of the economy and the relations of these sectors as sellers to final consumers. The technique was introduced in 1936 by Wassily Leontief who modified and aggregated the Walrasian general equilibrium system [18] to produce a statistical description of the United States economy [19], derived from empirical observations of interindustry transactions. The Leontief formulation was the first operational economic model to embody the essence of general equilibrium. Applications of the theory since that time have resulted in the construction of input-output tables for more than fifty national economies and for an expanding number of regions and urban areas.

The model derives its name from the method by which it categorizes economic transactions. Each exchange of goods and services between sectors in the model is recorded in double entry fashion as both a sale of output and a purchase of input. The basic static version of the model is normally presented in the form of three types of tables: Transactions Table, Technical Coefficient Table, and Table of Direct and Indirect Requirements.

THE INPUT-OUTPUT MODEL IN SUMMARY

The first of these three tables, the Transactions Table, is based upon a set of accounting identities or balance equations which state that the aggregate sales of a particular sector are equal to the total purchases from that sector. Given an economy divided into n sectors, the balance equations take the form

$$X_i = x_{i1} + \dots + x_{in} + Y_i \qquad (i = 1, \dots, n) \qquad (1)$$

where

X_i = the total output of industry i,

x_{ij} = the amount of commodity i required by industry j, and

Y_i = the exogenous or final demand for commodity i.

Once value added (factor payments) and input flows are also recorded, the simple precept of the table that total inputs equal total outputs can be stated as

$$X_j = x_{1j} + \dots + x_{ij} + \dots + x_{nj} + v_j + m_j \qquad (j = 1, \dots, n) \qquad (2)$$

$$= X_i \qquad (i = j = 1, \dots, n)$$

where

X_j = total purchases made by sector j,

v_j = value added of sector j, and

m_j = purchases of imports by sector j.

The second table, the Table of Technical Coefficients, represents the model's structural equations which state the assumption of fixed technical coefficients a..., i.e., the assumption that inputs into each sector are a direct function of the level of output of that sector. Compared to the n balance equations, there are n^2 structural equations of the form

$$x_{ij} = a_{ij}X_j \qquad (i, j = 1, \ldots, n) \qquad (3)$$

where

X_j = the total output of industry j, and

a_{ij} = the technical coefficient defined by x_{ij} and X_j above.

The model's second table is thus the $[a_{ij}]$ matrix.

To derive the third and most useful table, the Table of Direct and Indirect Requirements, the structural Equation 3 is first substituted into the balance Equation 1. This substitution results in

$$X_i = a_{i1}X_1 + \ldots + a_{ij}X_j + \ldots + a_{in}X_n + Y_i \qquad (i = 1, \ldots, n) \qquad (4)$$

which may be written more compactly in matrix form as

$$X = AX + Y$$

or

$$X - AX = (I - A)X = Y$$

where $A = [a_{ij}]$ and I is an identity matrix.* The general solution, by matrix inversion**, may now be expressed as

$$X = (I - A)^{-1} Y \quad .$$

---

*An identity matrix is a matrix whose principal (NW-SE) diagonal is composed of unit values and whose off-diagonal elements are zeros.

**Inversion is the counterpart of division in matrix algebra. The inverse of any matrix A is defined as that matrix which when premultiplied or postmultiplied by the original matrix A will yield an identity matrix. Thus $AA^{-1}A = 1$.

The matrix A in the previous notation is the Table of Technical Coefficients derived from the Transactions Table in the manner previously described. The "Leontief inverse," $_T(I - A)^{-1}$, is the third table and is customarily transposed*, $(I - A)^{-1}$, in order that the relevant information can be read along the rows rather than down the columns.

The Table of Direct and Indirect Requirements answers the question of how much output must be produced in order to satisfy final demands. If steel is the commodity in question, the economy will have to produce:

as much steel as consumers will use directly;

plus as much steel as is needed to produce other final consumer products;

plus as much steel as is needed to produce the inputs for these final consumer products;

plus as much steel as is needed to produce the inputs which are in turn used to manufacture those inputs which go into those final products;

plus as much steel as is needed for the inputs to make the inputs for the final products;

and so on, ad infinitum. [20]

Gross regional product, the regional counterpart of GNP, can be calculated from the input-output model by either of the two usual methods. The income or factor payments approach can be undertaken by summing the value added flows for each of the intermediate and final demand sectors. On the other hand, the same result can be obtained via the sales of final product approach by summing the total purchases of each final demand sector, subtracting out imports.

DEVELOPMENT OF THE MODEL

The Nine-County Bay Area Model for 1963 was developed from secondary data sources which were used to proportion or otherwise aid in the estimation of Gross Output values of production for the major sectors of the regional economy [14]. The elements of the final demand vectors were similarly proportioned on the basis of available data [14]. The interindustry transactions table was prepared by means of a FORTRAN IV computer program developed for this purpose [21]. This program is essentially a computerized version of the "Moore-Petersen" method described in their article dealing with the construction of an input-output table for the economy of the State of Utah [22]. The basic input-coefficients used were those of the CEIR/Fortune study describing the structure of the U. S. economy for 1966 [23]. The sector aggregation is shown in Table III and was chosen to emphasize those industries known to be waste-intensive and to discharge major waste constituents, either conservative (nondegradable) or nonconservative (degradable), which result in substantial quality degradation of the receiving waters.

The interindustry transactions table for the 9-county region is shown as Table IV; the technical coefficient matrix, including value added coefficients (Table V) succeeds the flow table; the table of direct and indirect requirements per dollar of output to final demand is shown finally as Table VI.

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*A matrix is transposed by interchanging its rows and columns.

TABLE III

SECTOR CLASSIFICATION FOR THE MODEL

Industry No. and Industry Title	Related 1966 National Input-Output Sectors from CEIR Study [23]
Rows	
1 Agriculture, Forestry and Fisheries	1, 2, 3, 4
2 Mining	5, 6, 7, 8, 9, 10
3 Construction	11, 12, 13, 14, 15, 16, 17, 18
4 Food and Kindred Products	20, 21, 22, 23, 24, 25, 26, 27, 28
5 Paper and Allied Products	38, 39
6 Chemicals and Chemical Products	41, 42, 43, 44
7 Petroleum Refining and Related Industries	45
8 Stone and Clay Products	50
9 Fabricated Metal Products	55, 56, 57, 58
10 All Other Manufacturing	19, 29, 30, 31, 32, 33, 34, 35, 36, 37, 40, 46, 47, 48, 49, 51, 52, 53, 54, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80
11 Transportation, Communication, Electric, Gas and Sanitary Services	81, 82, 83, 84, 85, 86
12 Wholesale and Retail Trade	87
13 Finance, Insurance and Real Estate	88, 89
14 Services and Government Enterprises	90, 91, 92, 93, 94, 95, 96, 97, 99, 100, 101
15 Interindustry Inputs	
16 Sectoral Imports	
17 Foreign Imports	
18 Total Sectoral Imports	
19 Value Added	
20 Adjustment	
21 Total Gross Outlay	
Columns	
1-14 Same as above (Rows)	
15 Intermediate Outputs – Total	
16 Personal Consumption Expenditures	
17 Gross Private Capital Formation	
18 Federal Government Expenditures	
19 State and Local Government Expenditures	
20 Net Exports	
21 Total Final Demand (Sum of Row Elements of Columns 16-20)	
22 Total Gross Outputs	
23 Commodity Imports	

TABLE IV

INTERINDUSTRY TRANSACTIONS TABLE (FLOW OF GOODS AND SERVICES BY INDUSTRY OF ORIGIN AND DESTINATION) 1963
NINE BAY AREA COUNTIES
(All figures in millions of dollars)

Column	1	2	3	4	5	6	7	8
Row 1	54.43	0.00	3.26	317.31	0.00	0.31	0.00	0.03
Row 2	0.08	0.40	2.64	0.20	0.21	1.11	62.63	1.26
Row 3	6.59	0.05	0.45	10.49	1.25	0.87	2.40	0.13
Row 4	35.69	0.00	0.54	527.93	1.59	9.98	1.12	0.21
Row 5	0.34	0.11	14.18	44.79	71.25	13.25	6.54	9.48
Row 6	9.91	0.72	61.49	16.13	9.07	121.02	45.82	9.28
Row 7	9.30	0.65	62.88	11.76	3.08	18.27	116.67	2.66
Row 8	0.24	0.41	182.79	19.43	1.07	4.26	2.73	23.67
Row 9	1.03	0.36	288.96	66.99	2.89	8.38	23.89	3.00
Row 10	6.05	3.15	459.69	23.04	22.44	17.12	2.82	8.15
Row 11	12.76	3.59	123.83	141.60	17.60	27.80	114.86	24.79
Row 12	18.00	1.73	304.91	107.53	12.26	15.90	17.32	9.70
Row 13	26.51	7.77	41.27	28.50	3.73	10.24	23.75	5.03
Row 14	12.71	2.34	172.26	185.83	7.12	41.14	44.13	9.20
Row 15	193.64	21.27	1719.16	1501.51	153.55	289.66	464.68	106.59
Row 16	114.11	6.14	315.08	683.28	31.87	52.09	786.55	31.21
Row 17	10.84	7.63	0.00	108.83	20.90	9.85	51.36	2.77
Row 18	124.96	13.77	315.08	792.11	52.78	61.93	837.91	33.99
Row 19	214.34	46.47	1435.81	777.95	120.84	217.55	315.22	112.63
Row 20	0.07	0.00	0.03	-0.02	0.00	-0.01	0.00	42.03
Row 21	533.01	81.51	3470.07	3071.56	327.17	569.13	1617.81	295.24

Column	9	10	11	12	13	14	15	16
Row 1	0.00	25.75	0.49	1.83	34.39	12.14	449.96	58.77
Row 2	0.03	4.71	5.90	0.02	0.51	0.79	80.48	0.74
Row 3	0.44	8.98	89.31	28.75	270.57	111.51	531.79	0.00
Row 4	0.01	2.82	4.24	22.24	2.81	124.54	733.71	1725.23
Row 5	4.73	74.60	2.26	22.93	5.69	31.05	301.19	25.32
Row 6	5.61	98.20	3.50	7.54	5.18	42.55	436.01	117.77
Row 7	3.21	14.41	72.87	27.49	21.87	20.88	386.00	266.42
Row 8	3.85	31.22	1.05	6.63	0.86	8.16	286.36	8.88
Row 9	56.90	124.02	7.10	6.42	0.83	8.37	579.13	14.75
Row 10	204.04	1424.80	72.37	50.47	35.18	531.29	2860.60	1294.10
Row 11	17.60	155.62	297.67	121.57	77.89	425.20	1560.39	748.36
Row 12	23.25	181.37	54.67	57.33	61.04	132.48	997.50	2300.30
Row 13	8.67	70.18	91.60	245.27	523.61	260.22	1346.35	2192.00
Row 14	16.93	165.45	261.93	340.27	225.18	427.13	1911.63	1560.61
Row 15	325.28	2380.12	964.97	938.77	1265.61	2136.31	12461.11	10313.24
Row 16	66.75	579.57	96.40	29.61	87.86	200.88	3083.19	516.76
Row 17	3.67	137.02	51.26	1.08	3.77	61.50	468.47	134.00
Row 18	72.48	714.38	147.65	30.69	91.63	262.37	3551.66	650.76
Row 19	263.71	2046.65	1718.94	2571.89	2785.64	2516.16	15143.81	76.00
Row 20	-0.01	-32.38	0.02	-4.35	0.01	0.02	0.00	0.00
Row 21	661.40	5108.78	2831.58	3537.00	4142.89	4914.86	31162.01	11040.00

Column	17	18	19	20	21	22	23
Row 1	0.00	20.38	3.90	0.00	83.05	533.01	-1066.97
Row 2	0.00	0.26	0.04	0.00	1.03	81.51	-998.57
Row 3	1533.84	253.74	650.30	520.50	2938.28	3470.07	0.00
Row 4	0.00	6.71	8.47	597.44	2337.85	3071.56	0.00
Row 5	0.00	0.65	0.00	0.00	25.98	327.17	-92.61
Row 6	0.00	10.15	5.20	0.00	133.12	569.13	-121.74
Row 7	0.00	149.30	14.94	801.15	1231.81	1617.81	0.00
Row 8	0.00	0.00	0.00	0.00	8.88	295.24	-100.84
Row 9	11.59	4.90	1.01	0.00	82.27	661.40	-164.68
Row 10	260.02	669.15	24.90	0.00	2248.18	5108.78	-1385.85
Row 11	0.38	49.52	44.71	428.22	1271.19	2831.58	0.00
Row 12	0.59	54.48	7.19	197.14	2539.50	3537.00	0.00
Row 13	0.19	4.45	17.08	582.82	2796.54	4142.89	0.00
Row 14	0.00	264.01	81.23	597.38	3003.23	4914.86	0.00
Row 15	1856.41	1967.72	838.87	3724.66	18700.90	31162.01	-3931.26
Row 16	55.27	229.03	16.42	0.00	848.07	3931.26	0.00
Row 17	-0.00	143.00	-0.00	0.00	277.00	745.47	745.47
Row 18	85.87	372.03	16.42	0.00	1125.07	4676.73	4676.73
Row 19	-0.00	846.20	949.50	0.00	1891.70	17035.51	0.00
Row 20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Row 21	1942.27	3805.95	1804.79	3724.66	21717.67	52879.68	0.00

TABLE V

INTERINDUSTRY TRANSACTIONS - TECHNICAL COEFFICIENT MATRIX
(DIRECT PURCHASES PER DOLLAR OF OUTPUT) 1963
NINE BAY AREA COUNTIES

Column Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	.102118	.000150	.012364	.066959	.000638	.018593	.017448	.000450	.001932	.011351	.023940	.033770	.049736	.023846
2	.000000	.004907	.000613	.000000	.001350	.008833	.007974	.005030	.004417	.038646	.044044	.021224	.095326	.028708
3	.000939	.000761	.000130	.000156	.004086	.017720	.018121	.052676	.083272	.132473	.035685	.087869	.011893	.049642
4	.103306	.000065	.003415	.171877	.014582	.005251	.003829	.006326	.021810	.007501	.046100	.035008	.009279	.060500
5	.000000	.000642	.003821	.004860	.217777	.027723	.009414	.003270	.008833	.068588	.053795	.037473	.011401	.021762
6	.000545	.001950	.001529	.017536	.023281	.212640	.032102	.007485	.014724	.030081	.048846	.027937	.017992	.072286
7	.000000	.038713	.001483	.000692	.004043	.028322	.072116	.001687	.014767	.001743	.070997	.010706	.014680	.027278
8	.000102	.004268	.000440	.000711	.032109	.031432	.009010	.080172	.010161	.027605	.083966	.032855	.017037	.031161
9	.000000	.000045	.000665	.000015	.007151	.008482	.004853	.005821	.055791	.308497	.026610	.035153	.013109	.025597
10	.005040	.000922	.001758	.000552	.014602	.019222	.002821	.006111	.024276	.278892	.030070	.035502	.013737	.032385
11	.000173	.002084	.031541	.001497	.000798	.001236	.025735	.000371	.002507	.025558	.105125	.019307	.032349	.092503
12	.000517	.000006	.008128	.006288	.006483	.002132	.007772	.001874	.001815	.014269	.034371	.016209	.069344	.096203
13	.008501	.000123	.065309	.000678	.001373	.001250	.005279	.000208	.000200	.008492	.018801	.014734	.126388	.054353
14	.002470	.000161	.022688	.025339	.006318	.008657	.004248	.001660	.001703	.108099	.086513	.026955	.052946	.086906
Value Added	.402000	.570000	.413000	.253000	.369000	.382000	.195000	.381000	.399000	.400000	.607000	.727000	.672000	.512000

TABLE VI

INTERINDUSTRY TRANSACTIONS
(DIRECT AND INDIRECT REQUIREMENTS PER
DOLLAR OF FINAL DEMAND) 1963
NINE BAY AREA COUNTIES

Column Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.1257377	.0014450	.0227859	.0940684	.0059143	.0310855	.0259002	.0034072	.0088859	.0411286	.0511295	.0510873	.0769752	.0572601
2	.0020415	1.0057358	.0122419	.0027093	.0051056	.0154245	.0128501	.0071488	.0086716	.0738407	.0647559	.0315057	.1202800	.0543914
3	.0038486	.0025797	1.0090003	.0055309	.0165408	.0356059	.0268371	.0609736	.0980170	.2526979	.0772794	.1118169	.0398355	.0951910
4	.1418294	.0009754	.0144762	1.2235754	.0268957	.0169711	.0129889	.0105214	.0326736	.0564510	.0885285	.0602242	.0385312	.1088510
5	.0027524	.0020913	.0125941	.0115447	1.2847728	.0515907	.0195323	.0072379	.0189491	.1497220	.0982190	.0627345	.0339627	.0615460
6	.0059168	.0048674	.0121612	.0325249	.0432461	1.2790256	.0498335	.0128036	.0262243	.0968153	.0997091	.0521406	.0469916	.1298961
7	.0011541	.0425126	.0085765	.0039882	.0087106	.0419648	1.0834561	.0036276	.0199584	.0302615	.1001394	.0210553	.0335531	.0541112
8	.0017531	.0058365	.0092043	.0051416	.0490855	.0492868	.0176986	1.0892344	.0166231	.0734180	.1223092	.0490701	.0379841	.0667349
9	.0037389	.0012000	.0081485	.0039876	.0213395	.0262098	.0113349	.0110643	1.0735284	.4783377	.0629105	.0622952	.0366452	.0663207
10	.0092652	.0020[illegible]9	.0095076	.0055465	.0300076	.0386790	.0095691	.0110449	.0392245	1.4253644	.0659165	.0607990	.0371659	.0725793
11	.0023813	.0039001	.0432239	.0068553	.0050465	.0080486	.0344758	.0040335	.0100236	.0749945	1.1416373	.0350928	.0564145	.1305666
12	.0035446	.0007492	.0194331	.0123786	.0115349	.0073242	.0124605	.0040659	.0061442	.0503218	.0594225	1.0277406	.0935185	.1251845
13	.0118946	.0008097	.0793564	.0050444	.0050123	.0070868	.0107236	.0055575	.0093356	.0482349	.0414053	.0309178	1.1570775	.0844766
14	.0092847	.0012189	.0362073	.0367358	.0153049	.0202290	.0121906	.0061391	.0121889	.1912230	.1270830	.0484802	.0828612	1.1324392

FINAL DEMAND VECTORS AND PROJECTION TO TARGET YEARS

The categories of final demand shown in the Transactions Table for the 9-county Bay region were added to form a single final demand vector. This vector is a column vector of fourteen elements, corresponding to the 14 productive sectors specified in the Transactions Table.

For projection purposes each element was assumed to increase by 3 percent and 6 percent per year to the selected target years shown in Tables VII and VIII. The tables show the values resulting from the compounding of the elements of the vector from the base year. The assumptions build in a fixed pattern of expenditures and expected upper and lower bounds for the growth rate in real terms. Nevertheless, in view of historical growth trends, such simple basic assumptions seemed to be appropriate to the task of determining some ranges for effluent discharges in future years. If effluent discharge conditions implied by these projections are in fact worse, as indeed they may be, then additional measures for pollution abatement will have to be implemented.

TABLE VII

FINAL DEMAND PROJECTIONS — 3% GROWTH RATE
(Used as Minimum Expected Growth Rate in
Linear Programming Model, $\$10^6$)

Year / Sector	1963	1968	1970	1975	1980	1990
1	83.05	96.25	102.15	118.32	137.03	183.54
2	1.03	1.19	1.27	1.47	1.70	2.28
3	2,938.28	3,405.46	3,614.08	4,187.04	4,848.16	6,493.60
4	2,337.85	2,709.57	2,875.55	3,331.44	3,857.45	5,166.65
5	25.98	30.11	31.95	37.02	42.87	57.41
6	133.12	154.28	163.74	189.70	219.65	294.19
7	1,231.81	1,427.66	1,515.13	1,755.33	2,032.49	2,722.30
8	8.88	10.29	10.92	12.65	14.65	19.62
9	82.27	95.35	101.19	117.23	135.74	181.82
10	2,248.18	2,605.64	2,765.26	3,203.66	3,709.50	4,968.48
11	1,271.19	1,473.31	1,563.56	1,811.44	2,097.46	2,809.33
12	2,539.50	2,943.28	3,123.58	3,618.78	4,190.17	5,612.29
13	2,796.54	3,241.19	3,439.74	3,985.07	4,614.29	6,180.35
14	3,003.23	3,480.74	3,693.97	4,279.60	4,955.33	6,637.14

TABLE VIII

FINAL DEMAND PROJECTIONS – 6% GROWTH RATE
(Used as Maximum Expected Growth Rate in Linear Programming Model, $\$10^6$)

Year Sector	1963	1968	1970	1975	1980	1990
1	83.05	111.29	124.57	167.76	224.23	402.79
2	1.03	1.38	1.54	2.08	2.78	4.99
3	2,938.28	3,937.29	4,407.42	5,935.32	7,933.35	14,250.66
4	2,337.85	3,132.72	3,506.77	4,722.46	6,312.19	11,338.57
5	25.98	34.81	38.97	52.48	70.14	126.00
6	133.12	178.38	199.68	268.90	359.42	645.63
7	1,231.81	1,650.62	1,847.71	2,488.25	3,325.88	5,974.28
8	8.88	11.90	13.32	17.94	23.98	43.06
9	82.27	110.24	123.40	166.18	222.13	399.00
10	2,248.18	3,012.56	3,372.27	4,541.32	6,070.09	10,903.67
11	1,271.19	1,703.39	1,906.78	2,567.80	3,432.21	6,165.27
12	2,539.50	3,402.93	3,809.25	5,129.79	6,856.65	12,316.57
13	2,796.54	3,747.36	4,194.81	5,649.00	7,550.65	13,563.22
14	3,003.23	4,024.33	4,504.84	6,066.52	8,108.72	14,565.66

The principal merit of this method of projection is that the results obtained are consistent with one another, given the technological structure of the regional economy. It is highly unlikely that single industry projections based on the extrapolation of trends or other methods will give a set of consistent projections in which the underlying interrelationships of the regional economy are taken fully into account.

VII. WASTE WATER DISPOSAL INTO SAN FRANCISCO BAY

TYPES OF WASTE AND SPECIFIC CATEGORIES OF POLLUTANTS

There are three major types of polluted waters entering San Francisco Bay. These are: municipal and domestic wastes, industrial discharges, and return flows from irrigation and drainage, including surface wash or natural runoff after periods of precipitation.

Municipal and domestic wastes generally have high levels of biological oxygen demand (BOD) and can also pose health hazards if pathogens are present in large numbers, as may frequently be the case. Domestic wastes may also contribute nitrogen and phosphorus in quantities large enough to cause excessive algal growth.

Agricultural return waters and surface wash may carry dissolved salts, nutrients, or biostimulants from the leaching of fertilizers and soil constituents, and may also contain pesticides and other conservative pollutants that may be toxic to aquatic life.

Industrial waste waters can contain a spectrum of exotic pollutants about which very little may be known concerning their combined (synergistic) toxic effects in the receiving waters.

The major pollutants or waste constituents that are herein given attention are as follows:

BOD - Biological oxygen demand, the capacity for a waste to deplete the dissolved oxygen (DO) from the receiving water.

Nitrogen - In combination with phosphorus and sunlight, will cause algal growth, i.e., eutrophication.

Phosphorus - In combination with nitrogen, will react as stated above.

Phenol - A caustic poisonous acidic compound; toxic even when highly diluted.

TSS - Total suspended solids - material which might be removed by settling, consisting of decomposable organic matter or inorganic matter.

Oil and Grease - All oils, products of petroleum, and hydrocarbons.

Gross Heavy Metals - Metal particles in suspension, such as copper, lead, cadmium, zinc, iron, chromium, etc.

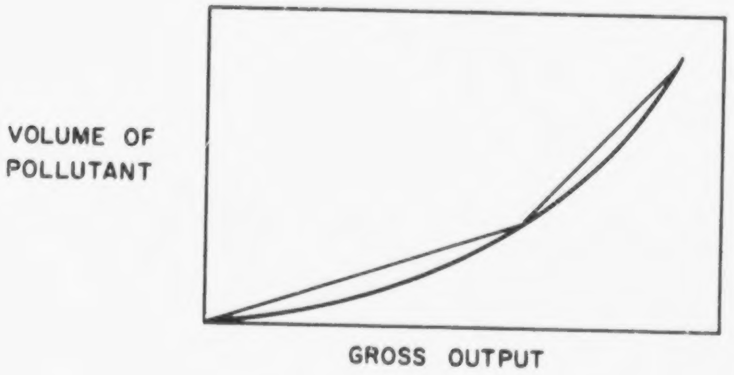
WASTE LOAD COEFFICIENTS

> "The idea of integrating the aspects of water resource requirements with those of the economy as a whole for a given area, be it a nation, a state, or an estuary, was pointed out in the early 1950's. The advantages accruing to the evaluation of both water resources and other resources of a region from the use of a combined accounting system, which also incorporates regional income and product accounts with the interindustry aspects of the intermediate transactions within the area and with other regions with which it trades, were since then recognized. The implementation of such models lagged

behind the need for obvious reasons. One was the operational difficulty in marshalling the vast quantities of consistent data on both the traditional aspects of the economy and on water-related accounts. Others were related to methodological difficulties in processing the data in a consistent manner within the framework of the input-output model.

> ".... The input-output model ... aims, in the long run, to relate the economy of a ... region to its environment in as complete a manner as possible. Such a model will cover in detail, the various inputs -- air, water, and other materials -- used by each industry. It will also identify all the various outputs furnished to the environment, such as steel and other economic goods, and discharged water and water pollutants.... The development of such a model attempts to achieve a much more complete accounting framework than is now possible. It would enable the evaluation of national and regional policies concerned with the quality of the environment as well as the state of the economy." [24]

In a manner similar to the construction of labor or water use coefficients, water quality or waste load coefficients may also be developed. As a first step it is necessary to develop for each economic sector the appropriate waste load coefficient to express the production of the particular pollutant in terms of commodity production. A linear relationship is assumed and such a coefficient is determined by dividing the total amount of the pollutant produced by the sector during the base period of the input-output table by the sector's gross output. In the event a nonlinear relationship is found to exist, piecewise linear approximations may be incorporated, as illustrated below.



Empirically, waste load coefficients for the seven waste constituents under consideration were calculated as shown in Tables IX – XII. The procedure of calculation of these coefficients for the agricultural sector is presented in Table XIII.

TABLE IX

PROCEDURE OF CALCULATION OF WASTE LOAD COEFFICIENTS[a]

Sectoral Daily Waste Flow mgd	Annual Sectoral Waste Flow mg	Annual Waste Flow / Annual Production gal/ton	Annual Production ton	Waste Load Coefficient of Pollutant lb/ton	Total Waste Production of Pollutant lb	Gross Output $\$10^6$	Waste Load Coefficient of Pollutant lb/$\$10^6$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Given[b]	(1) x 365	Given[b]	$\frac{(2) \times 10^6}{(3)}$	Given[b]	(4) x (5)	From I/O Table	(6)/(7)

[a] Transformation of waste load coefficients expressed in terms of Annual Waste Load/Annual Production (lb/ton) into waste load coefficients in terms of Annual Waste Load/Annual Gross Output (tons/$\$10^6$).

[b] See Reference [25].

TABLE X

CALCULATION OF ANNUAL PRODUCTION (PHYSICAL UNITS) FOR USE IN CALCULATION OF WASTE LOAD COEFFICIENTS

Sector	Daily Effluent 12 counties mgd	Daily Effluent 9 counties mgd	Annual Effluent 10^6 x gal/yr	Annual Production 10^6 x ton/yr	Gross Output $\$10^6$
Food	67.3	53.2	19,500	2.48	3071.56
Paper		47.9	17,500	0.625	327.17
Petroleum		197.7	72,000	165.0 (barrels)	1617.81
Stone and Clay	14.0	12.4	4,540	7.8	295.24
Chemicals	72.4	66.5	24,200	0.68	569.13
Fabricated Metals	17.8	16.4	6,000	0.26	661.40
Other Manufactures					5108.58

TABLE XI

CALCULATION OF WASTE LOAD COEFFICIENTS

Sector		BOD	Nitrogen	Phosphate	Oil and Grease	TSS	Phenols	Gross Heavy Metals
Food	Waste Load Coefficient, lb/ton	17.40	2.30		3.05	38.60		
	Annual Waste Production, ton/yr x 10^3	19.54	2.60	0.15[a]	3.44	43.51		
	Waste Load Coefficient, ton/$\$10^6$	6.36	0.84	0.04	1.12	14.16		
Paper	Waste Load Coefficient, lb/ton	33.0	0.87			51.50		
	Annual Waste Production, ton/yr x 10^3	9.3	0.24	0.23[a]		14.63		
	Waste Load Coefficient, ton/$\$10^6$	28.42	0.73	0.72		4.47		
Petroleum	Waste Load Coefficient, lb/10^3 barrel	131.0	74.2	0.87	31.5	111.3	9.1	1.57
	Annual Waste Production, ton/yr x 10^3	9.82	5.56	0.065	2.36	8.34	0.68	0.12
	Waste Load Coefficient, ton/$\$10^6$	6.07	3.44	0.04	1.46	5.16	0.42	0.07
Stone	Waste Load Coefficient, lb/ton					1.26	0.0001	
	Annual Waste Production, ton/yr x 10^3		0.008[a]		0.0003	4.45	0.0003	
	Waste Load Coefficient, ton/$\$10^6$	2.80	0.03		0.001	15.07	0.001	
Chemicals	Waste Load Coefficient, lb/ton	2.44	13.90	0.15	1.58	146.50	0.004	2.15
	Annual Waste Production, ton/yr x 10^3	0.75	4.29	0.04	0.48	45.28	0.0012	0.66
	Waste Load Coefficient, ton/$\$10^6$	1.31	0.75	0.08	0.84	79.56	0.002	1.16
Fabricated Metals	Waste Load Coefficient, lb/ton	0.94						
	Annual Waste Production, ton/yr x 10^3	0.11	0.14[a]					
	Waste Load Coefficient, ton/$\$10^6$	0.17	0.21					

[a] Calculation of pollutant annual waste production is based on waste load per employee coefficient (lb/day/employee).

TABLE XII

INDUSTRIAL WASTE LOAD COEFFICIENTS

SIC Code	Industry Group	Annual Waste Load/Annual Output							
		BOD[a] ton/$\$10^6$	Nitrogen ton/$\$10^6$	Phosphates ton/$\$10^6$	Oil and Grease ton/$\$10^6$	TSS[b] ton/$\$10^6$	Phenols ton/$\$10^6$	Gross Heavy Metals ton/$\$10^6$	Total[c] Effluent acre-ft/$\$10^6$
20	Food	6.36	0.84	0.04	1.12	14.16	-	-	7.26
26	Paper	28.42	0.73	0.72	-	4.47	-	-	88.70
28	Chemicals	1.31	0.75	0.08	0.84	79.56	0.002	1.16	33.46
29	Petroleum	6.07	3.44	0.04	1.46	5.16	0.42	0.07	18.97
32	Stone and Glass	2.80	0.03	-	0.001	15.07	0.001	-	22.76
34	Fabricated Metals	0.17	0.21	-	-	-	-	-	10.84
	All Other[d] Manufacturing	-	0.05	0.01	-	0.62	-	-	1.01

[a] Biological Oxygen Demand.

[b] Total Suspended Solids.

[c] Total process effluent — excluding cooling purposes.

[d] Assuming "All Other Manufacturing" adds 5% of the waste production in each polluting category.

TABLE XIII

CALCULATION OF AGRICULTURAL WASTE LOAD COEFFICIENTS

Sector	Annual Waste Production		Gross Output	Waste Load Coefficient	
	Nitrogen[a] 10^6 x lb/yr	Effluent[a] acre-ft/yr	$\$10^6$	Nitrogen ton/$\$10^6$	Effluent acre-ft/$\$10^6$
Agriculture	23.0	40,000	533.01	21.58	75.05

[a] See Reference [10].

To this point, only waste resulting directly from economic activities has been considered. Additionally, however, estuarine waters customarily receive pollutant flows from natural runoff waters and from discharge of domestic wastes.

Natural runoff pollutants evolve from the passage of tributary waters over erodible soil surfaces such as unpaved streets and construction sites, and from exposed earth surfaces — primarily agricultural lands containing various fertilizers and animal waste products. The contribution to the deterioration of water quality from natural runoff, however, is for most categories of pollutants quite limited relative to other sources, as presented in Table XIV.

TABLE XIV

NATURAL RUNOFF WASTE PRODUCTION

	BOD	Nitrogen	Phosphorus	Oil and Grease	TSS	Effluent Coefficient
Annual Waste[a] Production 10^3 lb/yr	18,900	5,200	250	6,100	1,660	
Annual Waste Production ton/yr	8,000	2.3	0.11	2.76	752.8	
Annual Effluent acre-ft/yr						262,000[b]

[a] See Reference [26].

[b]	acre-ft/yr
South Bay	149,000
Central Bay	48,000
North Bay	65,000
Total	262,000

Domestic waste water flows emanating from sanitary fixtures, garbage disposals, washers, air conditioners, etc. constitute a prime source of some pollutant measures such as BOD (biological oxygen demand) and nitrogen. Waste load coefficients for domestic waste are given in Table XV.

TABLE XV

DOMESTIC WASTE PRODUCTION

	BOD	Nitrogen	Phosphate	TSS	Oil and Grease	Gross Heavy Metals
Daily Waste Load[a] Coefficient, lb/capita/day	0.17	0.043	0.008	0.10	0.025	0.004
Annual Waste Production, tons/yr	121,711	30,785	563	71,544	17,907	260

[a] See Reference [27].

EFFLUENT COEFFICIENTS

Inasmuch as waste water treatment plants have a limited capability for total removal of waste constituents, a certain upper limit for effluent from all sources discharging to the Bay has been set. If this limit is exceeded regardless of the general level of treatment being provided, then the permissible concentrations of major waste constituents may be violated.

Effluent coefficients for major waste discharge sources are presented in Tables XII – XIV. The method of calculation in each case is indicated directly in Tables XVI and XVII.

TABLE XVI

DOMESTIC EFFLUENT – 1963[a]

	Effluent Coefficient gal/capita/day	Population 10^6	Effluent Coefficient acre-ft/1,000 pop.	Annual Domestic Effluent acre-ft/yr
Single Dwelling	67	3.02	75.1	227,779
Multiple Dwelling	55	1.05	61.6	64,600
Total		4.07		291,379

[a] See Reference [27].

TABLE XVII

PROCEDURE OF CALCULATION OF INDUSTRIAL EFFLUENT COEFFICIENTS

Industrial Category	Effluent[a]		Total Annual Effluent		Process Effluent Coefficients	
	Process mgd	Total mgd	Process acre-ft/yr	Total acre-ft/yr	Output $\$10^6$	Coefficients acre-ft/$\$10^6$
Food	19.9	67.3	22,294	75,396	3,071.56	7.26
Paper	25.9	47.9	29,016	53,366	327.17	88.7
Chemicals	17.0	72.4	19,045	81,110	569.13	33.46
Petroleum	27.4	197.7	30,696	221,485	1,617.81	18.97
Stone and Glass	6.0	14.0	6,721	15,684	295.24	22.76
Fabricated Metals	6.4	17.8	7,170	19,941	661.40	10.84
Other Manufacturing	4.6		5,153		5,108.78	1.01

[a] See Reference [25].

Thus the data requirements as presented in Table XVIII became available for application to the water quality management model.

TABLE XVIII

WASTE LOAD AND EFFLUENT DATA REQUIREMENTS FOR WATER QUALITY MODEL

Category	Effluent Coefficient	Waste Load Coefficient
A. Domestic	x	x
B. Natural Runoff	x	x
C. Agriculture	x	x
D. Industry		
(1) Six Primary Polluters	x	x
(2) All Other Manufactures	x	x

A summary of waste load and effluent coefficients for agricultural return flow, natural runoff, and domestic waste is given in Table XIX.

TABLE XIX

WASTE LOAD AND EFFLUENT CHARACTERISTICS OF DISCHARGED EFFLUENT INTO SAN FRANCISCO BAY (EXCEPT INDUSTRIAL)

	BOD ton/yr	Nitrogen ton/yr	Phosphates ton/yr	Oil and Grease ton/yr	TSS ton/yr	Phenol ton/yr	Gross Heavy Metals ton/yr	Effluent acre-ft/yr
Agriculture[a] Return Flow	-	21.58	-	-	-	-	-	75.05
Natural Runoff[b]	8,000	2.3	0.11	2.76	752.8	-	-	262,000
Domestic[c] (1963)	121,711	30,785	563	17,907	71,544	-	260	291,379

[a] See Table XIII, this report.

[b] See Table XIV, this report.

[c] See Tables XV and XVI, this report.

VIII. QUALITY STANDARDS FOR SAN FRANCISCO BAY

IDEAL WATER QUALITY OBJECTIVES FOR THE BAY-DELTA REGION

The waters of the San Francisco Bay-Delta region provide innumerable amenities to the population for an entire spectrum of socioeconomic and aesthetic endeavors. Traditionally such endeavors have usually been considered "beneficial uses." Increasingly, however, concern about the ultimate habitability of the environment for both man and other forms of life is forcing the concept of ecological balance to supersede the narrower notion of a well-ordered list of "beneficial" attributes that stem from maintaining the natural qualities of estuarine waters. Ideally the water quality objectives for San Francisco Bay should be to maintain the ecological balance of the region in such a way as to permit the traditionally ordered list of "beneficial" uses for the water to be met as a necessary but not overriding objective. From this viewpoint, water quality management is imbued with stronger positive overtones than might otherwise be the case while at the same time giving consideration both to preservation of the environment and the urban-metropolitan economic structure of society.

PERMISSIBLE LEVELS OF CONCENTRATION OF POLLUTANTS

The fact that "water quality" has meaning only in terms of beneficial use makes it difficult to define objectives that approach the ideal and suggests that the foregoing concept of preservation of any given ecosystem while at the same time discharging waste effluents may be unattainable. However, just as PHS Drinking Water Standards permit certain concentrations of impurities which are evidently noninjurious to human health, so may certain levels of pollutants in estuarine waters be acceptable to a desirable ecosystem in the Bay; if not indeed to the ecosystem which might exist in the complete absence of the activities of urban man. The critical problem is to determine what quality constituents must be regulated and in what concentrations each is compatible with the water quality objectives enunciated for the Bay, either alone or in combination with other constituents.

Seven waste constituents are dealt with explicitly in this report. The permissible levels shown in Table XX were arrived at either by using generally established standards or, where necessary, by a variety of calculations modified or adjusted in the light of the judgment of others[*] who have long worked directly with problems of quality of the waters of San Francisco Bay. These values, however, represent concentrations of dispersed wastes that might currently be permissible in Bay waters. What might happen to the ecosystem of the Bay between the moment of discharge of any pollutant and its dispersion throughout the water mass is a matter of great concern in water quality management, particularly because not all creatures in the ecosystem are sufficiently mobile to protect themselves by simply avoiding a particular area of the Bay. On the other hand, there is no real way to attain the water quality objectives of the Bay except to limit the amounts of any pollutant which any given discharger may release to the Bay and under what conditions, inasmuch as the concept of permitting no discharge whatsoever is not yet compatible with the realities of the economic base of the national standard of living. This means that the mixing and dispersion concepts of basic hydraulics must be applied to the Bay System in order to relate specific source loads to concentration levels permitted in the receiving waters.

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[*] Most notably, Mr. Phillip N. Storrs, Engineering-Science, Inc.

TABLE XX

WATER QUALITY STANDARDS FOR SAN FRANCISCO BAY

	Current Concentrations in the Bay		Recommended Quality Objectives in the Bay mg/ℓ
	Minimum mg/ℓ	Maximum mg/ℓ	
BOD	1.0	12.0	11.0[c]
Nitrogen	0.23	0.35	2.0
Phosphates	0.1	1.9	0.1
Oil and Grease		< 1.0	2.0
TSS	12.0	18.0	12.0
Phenol			0.01
Gross Heavy[a] Metals		—	0.33
Effluent[b] (acre-ft/yr)			745,000

[a] See Reference [28].

[b] 140% of 1968 levels or maintaining projected 1980 levels.

[c] Based on calculations of rate of oxygen utilization with a minimum DO (Dissolved Oxygen) level of 5.0 mg/ℓ to maintain fish life.

STEADY STATE LINEAR OPTIMAL DISPERSION MODEL

Mukherjee [4] recognized this tendency to express water quality standards in terms of the maximum allowable concentration levels in the water resource itself, in contrast with the traditional limiting of the maximum quantity of each waste constituent that might be discharged to the body of water. To achieve the maximum allowable concentration resulting from any discharge, Mukherjee applied the technique of linear programming to basic hydraulic concepts. In describing this approach Mukherjee noted:

> "Specifically, an optimization model is presented (phase 4), based on a one-dimensional description of the dispersion process which includes both longitudinal dispersion and advection in an estuary. It can be used for an estuary where tidal effects are pronounced and downstream velocity is low, or for a fast-flowing river.
>
> "A steady state model is described in detail for quality conditions averaged over a tidal cycle."

From a theoretical viewpoint it may be considered that waste constituents either in solution or carried as suspended matter have the same advective velocity as that of the flowing water. The time rate of advective transport of waste constituent for any section of a water course is given by Q c, where Q is specified as the volume flow rate for the section and c is the concentration of the waste constituent expressed as mass per unit volume. If the waste constituent is of the conservative type then the above concepts present a ready means for estimating the concentration limits in any section of a water course if the original amounts discharged into the flowing water are known. For nonconservative waste constituents the time factor required for them to exhibit the degradable qualities must also be known. As the degradable (nonconservative) waste constituents are carried to a given section of the water course the travel time from the original source of discharge is thus also important if concentration limits of these types of constituents are to be calculated.

"Dispersion" is the generally-used term which implies the mixing which results from molecular diffusion along with that due to other factors such as turbulence, stratification, and other departures from one-dimensional flow due to shear flow. The resultant mixing in long channels (i.e., water courses) due to the above phenomena is usually termed "longitudinal dispersion."

With steady state assumptions the diffusion equation for a nonconservative substance has the form: [4]

$$AE \frac{dc}{dx} = Avc - \int_{o}^{x} (S - k\,Ac)\,dx \quad .$$

For a conservative substance, the form of the equation is:

$$AE \frac{dc}{dx} = Avc - \int_{o}^{x} S\,dx$$

where:

A = the average cross-sectional area

v = the average advective velocity

c = the average waste constituent concentration

E = the average longitudinal dispersion coefficient

k = first-order decay rate constant of a degradable constituent

S = net rate of discharge of constituent mass per unit length

x = longitudinal distance along the estuary.

Given the maximum allowable concentration of various waste constituents (set to achieve some predetermined goals) at different sections of an estuary the task is to find a scheme which determines the conditions for the maximum permissible total amount discharged for each constituent. This will yield conditions which will minimize the total amount of waste constituents that must be removed from waste discharge sources discharging directly to the receiving waters. This presumably will minimize treatment costs.

Mathematically:

$$\text{Find } D = \max \int_0^L S(x)dx, \; S \in S^{**}$$

and find the corresponding optimal discharge pattern $\tilde{S}(x)$. S^{**} is a set of feasible discharge patterns S which will satisfy the following equations and any other constraints which may additionally be imposed:

$$0 \le L_s(x) \le S(x) \le U_s(x) \quad , \quad x \in [0 , L]$$

and

$$0 \le c_s(x) \le U_c(x) \quad , \quad x \in [0 , L]$$

and

$$\frac{dc_s(x)}{dx} = a(x)c_s(x) - b(x) \int_0^x S(y)dy - T_o \, b(x) \quad , \quad x \in [0 , L]$$

where

$a(x) = v(x)/E$

$b(x) = 1/A(x)E$

T_o = actual amount of the constituent crossing into the boundary at $x = 0$

x = longitudinal section [0 , L]

$U_s(x)$ and $L_s(x)$ = the upper and lower bounds on the discharge rate from basic physical consideration, essentially to avoid high local concentrations near a specific outfall.

Alternative goals and corresponding costs may be evaluated by substituting different sets of values for $U_c(x)$.

In solving for steady state conditions for conservative constituents ($k = 0$) the equation

$$AE \frac{dc}{dx} = Avc - \int_0^x S \, dx$$

can be modified to a finite difference form by substituting

$$\left(\frac{dc}{dx}\right)_i = \frac{c_{i+1} - c_{i-1}}{x_{i+1} + x_i} \quad \text{and} \quad c_i = \frac{c_{i+1} + c_{i-1}}{2}$$

and simplifying to

$$c_{i+1} = d_i c_{i-1} - g_i \sum_{k=1}^{i} S_k - g_i F ; \qquad (i = 1, 2, \ldots, n-1)$$

with

$$f_i = A_i \left\{ \frac{E_i}{x_i + x_{i+1}} + \frac{v_i}{2} \right\}$$

$$g_i = \frac{2 (x_i + x_{i+1})}{A_i \{2 E_i - v_i (x_i + x_{i+1})\}} \qquad \begin{matrix} (i = 1, \ldots, n-1) \\ (\text{with } n \text{ sections}) \end{matrix}$$

$$d_i = g_i f_i$$

$$g_n = \frac{x_n}{A_n (E_n - x_n v_n)}$$

$$d_n = \frac{E_n}{E_n - x_n v_n}$$

where A_i, E_i, v_i, and c_i are the values at sampling station i.

The finite difference form of the equation can be further modified to permit its adaptation to a general programming model in which standard linear programming techniques can be used to find the optimal solution limits of constituent discharges as posed in the introductory portion of the report as being one of the two basic tasks of the research.

The equation system developed in the foregoing paragraphs applies to the case of a conservative constituent. A modification of the equations to include a decay term permits the formulation of a linear program for nonconservative constituents. (See Mukherjee [4] pp. 53 and 83.)

OPTIMAL ANNUAL LEVELS OF DISCHARGE OF POLLUTANTS INTO THE BAY

The data inputs for the linear programming model outlined in the preceding section are shown in Tables XXI and XXII. These data were taken from Volume VII of "A Comprehensive Study of San Francisco Bay" [29]. Optimal solutions were found for four nonconservative waste constituents and three conservative waste constituents. Linear programming models were set up and solved for the North Bay and South Bay for both summer and winter conditions (a total of 4 rotations) and for all seven constituents. Weighted annual averages were developed from the solutions of the linear programs as optimal quality requirements of waste discharge into San Francisco Bay, presented in Table XXIII, which were then set out as constraints (or right-hand sides) for a further overall programming model.

TABLE XXI

HYDROLOGICAL INPUT DATA FOR LINEAR PROGRAMMING DISPERSION MODEL IN NORTH BAY[a]

No.	Section[a] Number from Report	Cross-Sectional Area A_i 10^6 ft^2	Diffusion Coefficients E_i ft^2/sec	Length of Sections X_i 10^3 ft	Net Advective Velocities[b] V_i	
					Summer 10^{-3} ft/sec	Winter 10^{-3} ft/sec
1	16	1.34	4,800	4.5	- 0.149	2.24
2	17	2.52	3,000	12.2	0.108	4.60
3	18	1.44	4,500	19.6	0.341	6.65
4	19	1.00	2,400	12.3	0.414	6.80
5	20	1.13	1,400	22.6	0.914	5.39
6	21	1.15	900	25.7	3.76	9.90
7	22	0.50	1,030	18.9	7.62	14.0
8	23	0.32	1,300	32.6	6.38	11.2
9	24	0.33	800	14.1	5.76	9.44
10	25	0.41	500	9.5	5.75	9.01
11	26	0.58	250	14.1	6.35	7.10
12	27	0.43	400	15.6	10.9	11.2
13	28	0.23	700	17.2	11.7	11.7
14	29/31	0.24	1,000	26.0		

[a] See Reference [29], Tables XV – XVIII.

[b] Flow Seaward +
Flow Landward -

TABLE XXII

HYDROLOGICAL INPUT DATA FOR LINEAR PROGRAMMING DISPERSION MODEL IN SOUTH BAY[a]

Section	Cross-Sectional Area A_i 10^6 ft^2	Diffusion Coefficients E_i ft^2/sec	Length of Sections X_i 10^3 ft	Net Advective Velocities[b] V_i	
				Summer 10^{-3} ft/sec	Winter 10^{-3} ft/sec
1	2.6	4,800	18.0	- 1.02	3.98
2	2.35	4,800	19.1	- 1.19	1.38
3	1.67	550	19.6	- 1.46	1.55
4	1.80	700	21.3	- 1.36	1.17
5	1.95	900	21.0	- 1.17	1.06
6	1.47	700	27.6	- 0.963	0.977
7	0.68	1,000	15.6	- 1.48	1.60
8	0.57	1,400	11.7	- 1.23	1.12
9	0.39	1,000	20.5	- 1.18	1.24
10	0.22	553	16.0	- 1.71	2.45
11	0.15	378	10.5	- 0.363	1.95
12	0.06	307	7.5	1.22	4.28
13	0.04	207	9.3	1.99	4.45
14	0.02	331	5.4	6.72	8.16
15	0.01	1,170	16.5	10.3	12.1

[a] See Reference [29], Tables XV – XVIII.

[b] Flow Seaward +
Flow Landward -

TABLE XXIII

OPTIMAL QUALITY REQUIREMENTS OF WASTE DISCHARGE INTO SAN FRANCISCO BAY

	Recommended Quality Criteria mg/ℓ	Optimal Discharge into Bay		
		Summer lb/day	Winter lb/day	Total tons/yr
Conservative Constituents				
Oil and Grease	2.0	195,200	193,500	31,800
TSS	12.0	1,170,000	1,160,000	190,000
Gross Heavy Metals	0.33	32,600	32,300	5,300
Nonconservative Constituents[a]				
BOD	11.0	993,340	558,700	127,000
Nitrogen	2.0	469,130	263,886	59,895
Phosphates	0.1	9,930	5,588	1,270
Phenol	0.01	2,346	1,320	300
Total Effluent (acre-ft/yr)				745,000

[a] Decay factors used for summer k = 0.17/day and for winter k = 0.10/day.

The formats of the two linear programming models for conservative and nonconservative constituents are shown in Table XXIV.

TABLE XXIV

FORMAT OF STEADY STATE LINEAR PROGRAMMING DISPERSION MODEL

CONSERVATIVE CONSTITUENT

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	FD
R16	N																	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
R1	F	-1	1															*															
R2	F		-*	1														*	*														
R3	E			-*	1													*	*	*													
R4	E				-*	1												*	*	*	*												
R5	F					-*	1											*	*	*	*	*											
R6	F						-*	1										*	*	*	*	*	*										
R7	F							-*	1									*	*	*	*	*	*	*									
R8	E								-*	1								*	*	*	*	*	*	*	*								
R9	F									-*	1							*	*	*	*	*	*	*	*	*							
R10	F										-*	1						*	*	*	*	*	*	*	*	*	*						
R11	F											-*	1					*	*	*	*	*	*	*	*	*	*	*					
R12	F												-*	1				*	*	*	*	*	*	*	*	*	*	*	*				
R13	F													-*	1			*	*	*	*	*	*	*	*	*	*	*	*	*			
R14	E														-*	1		*	*	*	*	*	*	*	*	*	*	*	*	*	*		
R15	F															-*	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
upper bound		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*																

NONCONSERVATIVE CONSTITUENT

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	FD
R16	N																1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
R1	F	*	-*														-*															
R2	E	*	*	-*													-*	-*														
R3	F	*	*	*	-*												-*	-*	-*													
R4	F	*	*	*	*	-*											-*	-*	-*	-*												
R5	E	*	*	*	*	*	-*										-*	-*	-*	-*	-*											
R6	F	*	*	*	*	*	*	-*									-*	-*	-*	-*	-*	-*										
R7	F	*	*	*	*	*	*	*	-*								-*	-*	-*	-*	-*	-*	-*									
R8	E	*	*	*	*	*	*	*	*	-*							-*	-*	-*	-*	-*	-*	-*	-*								
R9	E	*	*	*	*	*	*	*	*	*	-*						-*	-*	-*	-*	-*	-*	-*	-*	-*							
R10	F	*	*	*	*	*	*	*	*	*	*	-*					-*	-*	-*	-*	-*	-*	-*	-*	-*	-*						
R11	F	*	*	*	*	*	*	*	*	*	*	*	-*				-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*					
R12	F	*	*	*	*	*	*	*	*	*	*	*	*	-*			-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*				
R13	F	*	*	*	*	*	*	*	*	*	*	*	*	*	-*		-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*			
R14	F	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*		
R15	E	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	
upper bound		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*																

IX. MULTICONSTITUENT WASTE WATER PROJECTION MODEL

ECONOMIC MULTIPLIER ANALYSIS

The study of the properties of an input-output model, as opposed to its use in making projections and predictions, is customarily classified as "structural" analysis. On the national level such analyses are often undertaken to compare interindustry relationships of one country with those of another, the comparison frequently being drawn between an underdeveloped and a developed nation [30]. Such analyses are also undertaken in connection with studies of the nation's balance of payments [31]. On the regional level, however, one of the major functions, if not the primary function, of structural analysis has been multiplier analysis, the study of the effects of changes in one part of the economic system upon other components as well as upon the system as a whole. Almost all such multiplier analyses have been confined to regions.*

The traditional Keynesian multipliers with their reliance upon the consumption function have always been defined in terms of highly aggregated variables. Income is generally treated as a single variable and no attempt is made to disaggregate on a sectoral basis.

> "By the nature of macroeconomics, its income-multiplier analysis is carried out strictly at the most general level. It does not ask who will produce the extra output when final demand is increased, or in which sector of the economy the additional national product is used. This kind of analysis is not enough to enable us to find out what will happen in individual industries .... This shortcoming of macroanalysis can be eliminated if input-output method is used instead. For input-output analysis deals with smaller parts of the economy than macroeconomics and its emphasis is on individual sectors, not on the national total." [34]

To illustrate the logic of the input-output multiplier, let us assume that within a regional economy industry i increases its output due to an upward shift of final demand for its product. As industry i expands production, it simultaneously increases its purchases of inputs. But since industry i's inputs are the outputs of other industries, these supplying industries also expand their production and purchases of inputs in view of increased output demand. Thus a chain-reaction expansion of production spreads throughout the economy.

Since the element r_{ij} of the matrix $(I - A)^{-1}$ reveals the output directly and indirectly required from industry j to support the delivery of one dollar of production to final demand by industry i, a dollar change in final demand for the product of industry i will result in a change in the output of industry j of r_{ij}.

Denoting v_j as the value added per dollar of gross output of industry j, the total change in gross regional product resulting from the initial increase in the final demand for the output of industry i may be calculated as

$$\Delta GRP = \sum_{i} v_j \, \Delta X_j = \sum_{i=1}^{n} v_i \sum_{j=1}^{n} r_{ij} \, \Delta Y_j$$

---

[*] An exception is the Leontief and Hoffenberg study [32]. The effects of disarmament on a regional basis, however, were later studied by Leontief, Morgan, Polenske, Simpson, and Tower [33].

and the multiplier [35] may be expressed as

$$M_i = \frac{\Delta GRP}{\Delta Y_i} = \frac{\sum_{i=1}^{n} v_i \sum_{j=1}^{n} r_{ij} \, \Delta Y_j}{\Delta Y_i} \qquad (i = 1, \ldots, n) \quad .$$

WASTE CONSTITUENT MULTIPLIER ANALYSES

In a manner similar to the construction of economic multipliers, water quality or pollutant load multipliers may also be developed from the input-output inverse matrix. As a first step it was necessary to develop for each economic sector the appropriate pollution coefficient to express the production of the particular pollutant in terms of commodity production, as discussed in Chapter VII.

Once such coefficients are established, pollutant multipliers can be derived through application of the coefficients to the Leontief inverse. For a regional economy of n sectors and a particular pollutant p, an n-element vector, ℓ_{jp} $(j = 1, \ldots, n)$, of load coefficients is constructed. For purposes of computation the vector is transformed into a diagonal matrix, ℓ^p_{kj}, by consecutively entering the vector's elements along the principal diagonal of an n order matrix (i.e., a matrix with n rows and n columns) whose off-diagonal elements are zeros. The resulting matrix is then premultiplied by the transposed Leontief inverse of the input-output model to yield the "pollutant content" matrix or table of pollutant production. Each entry, P_{ij}, in the table or matrix P reveals in units of volume the pollutant associated with, or "pollutant content" of, the output of industry j required by industry i for the latter industry to deliver one monetary unit of production to the final demand sector.

$$P_{ij} = \sum_{k=1}^{n} r_{ik} \, \ell^p_{kj} \qquad \begin{matrix} (i = 1, \ldots, n) \\ (j = 1, \ldots, n) \end{matrix}$$

where $[r_{ik}] = [r_{ij}]^T$.

The row sums of the above matrix P can then be summed to form pollutant load multipliers. An element m_i in the vector M_{ip} will represent the direct plus indirect production of the pollutant p associated with a change in the final demand of industry i.

$$M_{ip} = \sum_i \frac{\ell_{ip} \sum_{j=1} r_{ij} \, \Delta Y_j}{\Delta Y_i} = \sum_j \, [P_{ij}] = \sum_j \sum_{k=1}^{n} r_{ik} \, \ell^p_{kj} \quad .$$

The change in the final demand for industry i may for purposes here be grouped into three categories: 1) relatively small changes which do not result in alterations of the economy's structural relations; 2) larger changes necessitating or caused by changes in the technical structure; and 3) the entrance of new industries into the region. Pollutant load multipliers as formulated above are most easily and accurately calculated for the first category in which changes in final demand are not associated with technological change. Changes in either the interindustry structural relations or in water-use technology require corresponding adjustments in the Table of Technical Coefficients and in the pollutant load coefficients, respectively.

The waste load coefficients developed in Chapter VII can be used, based on the above concept, in conjunction with the "inverse matrix" of the input-output table to further develop waste constituent multipliers. The matrices relating direct and indirect changes of waste constituent output to unit changes in final demand have been termed "waste constituent interactions" tables. This terminology was adapted from the Moore and Petersen study of Utah [22] in which they develop employment or labor coefficients and by a similar procedure develop what they chose to call an "employment interactions" table.

WASTE CONSTITUENT INTERACTIONS TABLES

In the appendix are presented the "constituent interactions" tables for each of the 7 waste constituents and total effluent discharge dealt with in this report. Each table has been formed by postmultiplying the transposed Leontief inverse by a matrix of constituent discharges entered on the principal diagonal of the matrix with all off-diagonal elements being zero. The matrices are shown as the resulting product of the matrix multiplication and have not been transposed after the multiplication was carried out.*

The waste constituent multiplier effects of each Bay industry can be read directly from the tables. For example, if the final demand for the Paper and Allied Products (sector 5) in the Bay increases by $1 million, the industry in meeting the increase in final demand will be responsible for discharge (directly and indirectly) of 36.83 tons of BOD and 1.12 tons of nitrogen annually, etc. For convenience, the total waste constituent discharges from all industries due to a simultaneous change of $1 million in final demand in each industry are given in Table XXV.

TABLE XXV

SIMPLE AND WEIGHTED EFFLUENT AND WASTE MULTIPLIERS
FOR THE SAN FRANCISCO BAY REGION

	Simple Multipliers ton/$\$10^6$ of Total Final Demand	Weighted Multipliers ton/1% of Total Final Demand
BOD	5,145	418.37
Nitrogen	2,665	206.31
Phosphates	98	5.05
Oil and Grease	352	62.36
TSS	13,194	1,060.88
Phenol	0.041	6.66
Gross Heavy Metals	142	7.50
Effluent (acre-ft/$\$10^6$ of Total Final Demand)	26,500	1,599.03

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*This is emphasized because "in-core" operations with the computer can frequently lead to printout statements in which it is uncertain that a transpose has actually resulted.

CRITICAL TIME PERIOD ANALYSIS

The waste constituent multipliers developed in the previous section under conditions of existing treatment levels can be utilized for projecting future loads on the environment within the limitations outlined immediately above. This is accomplished by applying the multipliers to the projected final demand vector.

$$F_p^t = \sum_i M_{ip}^t \; Y_i^t$$

where F_p^t is the rate of discharge of effluent constituent or pollutant p through economic activity in year t. The accumulation of particular pollutant p within the environment at a point k years from the present, G_p^k, may now be expressed as

$$G_p^t = \sum_{t=1}^{k} \left(F_p^t + N_p^t + U_p^t - D_p^t \right) + F_p^o$$

where

N_p^t = the flow of pollutant p from natural runoff (pollutant weight/time),

U_p^t = the flow of pollutant p emanating from domestic effluent (pollutant weight/time),

D_p^t = the dispersive flow of pollutant p from the body of water into which it was expelled (pollutant weight/time),

F_p^o = the amount of pollutant p in the waters at time t = 0 (pollutant weight).

Once water quality standards for the estuary have been established as discussed in Chapter VIII and waste load multipliers in terms of the standards have been constructed, the multipliers can be applied to determine the critical time period which will elapse under the conditions of existing treatment operations before the quality standards are violated. Such a critical period T can be calculated from the following:

$$s_p = \sum_{t=1}^{T} G_p^t$$

where s_p is the quality standard pertaining to pollutant p in terms of pollutant weight.

An alternative method for calculating critical time periods employing weighted multipliers rather than simple multipliers was developed and applied in this report.

As defined previously, the multipliers do not reflect the relative importance of various sectors with regard to final demands upon their production. A $1 million increase in the level of final demand for the output of one sector in the Bay region may represent a rather insignificant increase relative to the same increase in demand for the production of another. The relative importance of each of the different sectors may therefore be reflected by 'weighting' the multipliers in regard to the total final demand for their outputs. This can be accomplished by calculating the total water withdrawal requirements resulting not from a $1 million increase in final demand but from an increase of one percent. Thus the new multiplier – the 'weighted multiplier' as opposed to the 'simple multiplier' – may be defined as follows:

$$\overline{M}_{ip} = \left(\sum_{i} r_{ji}\, e_{ip} \right) \Big/ (Y_i/100) \quad .$$

A summary of simple and weighted multipliers is given in Table XXV and the individual sectoral weighted multipliers are given in Table XXVI.

A method for calculating critical time periods using weighted multipliers was developed and used as follows:

$$L_p^t \quad = \quad L_p^o \quad + \quad \overline{M}_p \quad \times \quad 100\,q$$

$$\underset{[\text{tons}]}{\begin{bmatrix} \text{Waste Discharge} \\ \text{Limit of} \\ \text{Constituent } p \\ \text{in year } t \end{bmatrix}} = \underset{[\text{tons}]}{\begin{bmatrix} \text{Present Level} \\ \text{of Waste} \\ \text{Constituent} \\ \text{Discharge} \end{bmatrix}} + \underset{[\text{tons}/\frac{1}{100}]}{\begin{bmatrix} \text{Weighted} \\ \text{Multiplier} \\ \text{for} \\ \text{Constituent } p \end{bmatrix}} \times \underset{[1/100]}{\begin{bmatrix} \text{Maximum Possible} \\ \text{Increase in} \\ \text{Discharge of} \\ \text{Pollutant } p \end{bmatrix}}$$

This equation is solved for q and then substituted in the following equation to solve for t'

$$1 + q = (1 + r)^{t'}$$

where r is the expected annual growth rate of final demand.

If $t' \neq t$, another calculation for a different t is performed. After several trial and error calculations when $t \approx t'$ it represents the critical time period at which the expected discharge of constituent p is forecasted to violate the quality standards.

The resulting critical time periods for the various constituents due to the multiplier analysis is given in Table XXVII.

If one or more of the critical time periods calculated for the pollutants under consideration prove to be sufficiently short to warrant concern, the regional analyst may then turn to means of influencing the pollution process. The manner in which such influences may be exerted is the focus of the succeeding sections of this report.

TABLE XXVI

SECTORAL WEIGHTED EFFLUENT AND WASTE MULTIPLIERS FOR SAN FRANCISCO BAY REGION

Sector	BOD ton/1% F.D.[a]	Nitrogen ton/1% F.D.	Phosphates ton/1% F.D.	Oil and Grease ton/1% F.D.	TSS ton/1% F.D.	Phenol ton/1% F.D.	Gross Heavy Metals ton/1% F.D.	Effluent acre-ft/1% F.D.
1	0.82	20.33	0.01	0.09	3.35	0.01	0.03	72.57
2	0.003	0.001	-	-	0.01	-	-	0.02
3	34.67	7.34	0.53	2.06	123.10	0.30	1.17	182.16
4	204.49	97.45	1.63	32.72	445.20	0.12	0.47	546.39
5	9.21	0.28	0.23	0.02	2.57	0.002	0.01	29.22
6	4.68	1.75	0.17	1.57	136.88	0.03	1.97	65.08
7	85.55	46.78	0.61	19.94	112.02	5.53	1.47	285.22
8	0.68	0.02	0.003	0.006	1.83	-	0.004	2.78
9	1.80	0.33	0.02	0.04	2.26	0.003	0.02	12.84
10	24.95	8.09	0.90	1.12	98.69	0.09	1.01	156.91
11	5.59	2.41	0.08	0.81	13.22	0.18	0.15	23.77
12	13.20	3.55	0.25	0.96	24.37	0.13	0.23	52.56
13	8.11	8.67	0.14	0.75	23.21	0.11	0.25	58.43
14	24.62	9.31	0.48	2.28	74.17	0.15	0.72	111.08
Total	418.37	206.31	5.05	62.36	1,060.88	6.66	7.50	1,599.03

[a] F.D. = final demand.

TABLE XXVII

CRITICAL TIME PERIODS FOR POLLUTANTS DISCHARGED INTO SAN FRANCISCO BAY WITH 3% AVERAGE ANNUAL GROWTH RATE FOR FINAL DEMAND[a]

Critical Year \ Constituents	BOD	Nitrogen	Phosphates	Oil and Grease	TSS	Phenol	Gross Heavy Metals	Effluent
Without Flushing	1970	1972	1963	> 2000	1976	1963	> 2000	1974
With Flushing	1978	1982	1976	> 2000	1990	1965	> 2000	> 2000

[a] Based on untreated constituents weighted multipliers; i.e., no treatment of industrial waste is assumed.

X. LINEAR PROGRAMMING WATER QUALITY MANAGEMENT MODELS

INTRODUCTION

In order to achieve any specific estuarine water quality level with respect to the various polluting constituents, either at minimum costs or to ensure maximum regional economic growth, a linear programming water quality model can be formulated and applied to set up optional guidelines for water quality management. In this section of the report such a model is formulated and applied to the San Francisco Bay. In order to understand and evaluate its virtues and limitations, however, some discussion of the theory and mathematics of an optimizing approach may be in order.

AN OPTIMIZING APPROACH TO WATER QUALITY MANAGEMENT

One of the major objectives of resource management is the optimum utilization of the resources, i.e., to construct a plan of efficient allocation of the resources as related to a predetermined social objective. It is obvious that with a limited availability of a certain resource the continuous depletion of it should follow a plan of utilization which will ensure best results with respect to a certain objective within the availability constraints. Capital, foreign exchange, mineral resources, skilled labor, and water resources are some examples of scarce resources which are usually treated by this approach.

While the application of optimization techniques to water resources management is usually applied where constraints are imposed by the regional availability of either surface or ground water for beneficial uses (irrigation, municipal, and industrial), it seems only logical to apply a similar approach to water quality management where existing water bodies such as streams, lakes, estuaries, and ocean fronts serve as receiving waters for natural and human wastes. Thus, in terms of scarcity, quality of such water bodies may be considered as a natural resource useful for waste disposal purposes. The fact that this resource is scarce and deserves optimal allocation with respect to type and level of the pollutants discharged into it was demonstrated by the analysis in the preceding chapter which indicated that with a moderate growth of economic activity in the near future, and under present practices of waste treatment of the various waste productive units adjacent to the Bay, the minimum water quality criteria established for the Bay will soon be violated.

LINEAR PROGRAMMING AND MULTISECTOR MODELS

The general linear programming formulation and an iterative technique (the simplex method) for its solution were devised by George Dantzig in 1947. Since its conception linear programming has proved to be a powerful tool for achieving optimal solutions and has been successfully applied to a broad range of problems extending from those in welfare and development economics to problems in engineering and management operations.

Linear programming is a technique for optimization of a system in which all the relationships are linear. Given a set of m contraint equalities or inequalities in n variables, linear programming technique can find a set of nonnegative values of the unknown variables which will maximize or minimize an objective function. The objective function is an algebraic expression which is to be optimized, i.e., either maximized or minimized depending on the nature of the problem, and the constraints are mathematical statements of limitations beyond which, or outside of which, an objective is not feasible. The constraints define geometrically a solution space or feasible region within which is to be found the best, or optimal value, of the objective function.

Associated with every linear programming maximization problem is a directly related minimization problem, and vice versa. Choosing either the maximization or minimization problem to be designated as the "primal," the remaining problem is called the "dual." Duality is a mathematical property which relates the pair of problems one to another in the following way:

1. If the primal has a solution, so does the dual.
2. The optimum solution of the primal is equal to the optimum solution of the dual.
3. Solution of one problem leads to an immediate solution of the other.

The fundamental association between a maximization problem, arbitrarily designated as the "primal" problem and its dual minimization problem can be seen from the standard formulation:

Primal Problem	Dual Problem
Maximize $Z = \sum_{j=1}^{n} c_j X_j$	Minimize $Y = \sum_{i=1}^{m} b_i W_i$
Subject to: $\sum_{j=1}^{n} a_{ij} X_j \le b_i$	Subject to: $\sum_{i=1}^{m} a_{ij} W_i \ge c_j$
$X_j \ge 0$	$W_i \ge 0$

where

c_j is an n x 1 vector of constants,

X_j is an n x 1 vector of primal variables,

a_{ij} is an m x n matrix of constants,

b_i is an m x 1 vector of constants,

W_i is an m x 1 vector of dual variables.

The symmetry of the two linear programming problems can be highlighted by noting from the above formulation the following points:

1. If the primal problem involves maximization, the dual involves minimization, and vice versa.
2. If the primal constraints involve ≤ signs, the dual constraints involve ≥ signs, and vice versa.

3. The constants c_j in the primal problem replace the constants b_i in the dual problem, and vice versa.

4. In the constraint inequalities the matrix of constants $[a_{ij}]$ in the dual is the transpose of the matrix $[a_{ij}]$ of the primal.

5. A new set of variables appears in the dual.

6. Neglecting the number of nonnegativity conditions, if there are n variables and m inequalities in the primal problem, in the dual there will be m variables and n inequalities.

An economic interpretation of the dual variables is presented subsequently.

The techniques of linear programming and input-output analyses form a basis for the construction of economic models. Multisector models differ from L-P models, however, in the same way that positive economics differs from normative economics. The task of the former branch of economic science is to provide a system of hypotheses that can be utilized to derive estimations concerning the effects of changes in economic phenomena. The input-output multisector model can thus be labelled a positive or explication model. It is a set of functional relationships designed to reflect economic reality in such a way as to enable the analyst to make predictions regarding the effects upon the economic system of an impulse occurring somewhere within the system. The model does not incorporate target variables or optimizing procedures.

The linear programming model, on the other hand, can be related to the science of normative economics, that branch of economics which deals not with "what is" or "what will be" but with "what ought to be." It is a decision rather than an explication model and differs fundamentally from the input-output model in that it explicitly introduces goals into the problem formulation. These goals appear not only in the objective function but are included in the constraints as well.

Both approaches exclude the possibility of negative outputs evolving from productive processes and, due to the common assumption of linear economic relationships, both exclude also the possibility of external economies and diseconomies.

The fundamental difference in the basic assumptions of the two models stems from the fact that economic goals are incorporated into the linear programming model. The attainment of such goals implies choice among economic alternatives and it is this element of choice that is distinctive to programming. Even though it is possible for sophisticated versions of the input-output model to assume different linear production functions for different levels of output, the model must still rely for a particular range of output upon the assumption that each commodity is produced by a single production technique which produces no other commodities. The linear programming formulation differs, however, in that a) a single commodity may be the output of several different production processes, and b) a single production technique may have several outputs.

The linear programming model is thus the more general in that its assumptions are less restrictive. Moreover, its design is such that it can be applied within the decision-making process in such a manner as to incorporate the relevant information yielded by the input-output model. How this conjunctive use of the two techniques may be accomplished will be evident from the discussion in the following section.

WATER QUALITY MANAGEMENT MODELS

The use of optimization techniques for achieving a certain stream or estuary water quality level at minimum costs under certain economic and engineering constraints applying various pollution control methods is a relatively new development (since 1963). Models of controlling the BOD level in a river or an estuary to maintain a required DO concentration have been developed by Thomann [36,37]. Dissolved oxygen was also taken as the controlling parameter in the Delaware Estuary study by Sobel [38], as well as the study of costs of alternative methods for DO management in the Potomac River by Davis [39]. These studies applied linear programming model as their technique for optimization assuming linear relationships among the various parameters affecting the quality of these water bodies.

"A Linear Programming Water Quality Control Model" by J. Carew and P. H. McGauhey [3] was developed to illustrate a methodology to minimize the cost of achieving any water quality goal when the quantities of various wastes which were predicted by a separate input-output model served as inputs to the multicomponent water quality control model. The integration of a dispersion model with the model of water quality control to express preferred quality standards as the maximum allowable concentration levels in the water resource itself, was performed by S. K. Mukherjee [4], as discussed in a preceding chapter. The following model attempts to integrate these separate models into one programming model through the conjunctive use of input-output and linear programming techniques. With such a programming model as the basic tool, the various potential extensions and the empirical application of the model to the San Francisco Bay water quality management can be explored.

CONSTRAINTS

The water quality management model is, of course, subject to various constraints which establish the boundary conditions on the process of attaining the program's objectives. Assuming a regional economy of n sectors which discharge a total of m pollutants into the adjacent esturaine waters, the first set of constraints derive from the input-output model. These constraints state that once a portion of the gross output X_i of a particular sector i has been utilized to satisfy intermediate demands, $A\bar{X}$, upon that sector, there is sufficient output remaining to satisfy the final demands, Y_i^L, of the region.

$$X_i - \sum_{j=1}^{n} a_{ij} X_j \geq Y_i^L \qquad (i = 1, \ldots, n) \quad .$$

If for the moment Y_i^L is interpreted as being a vector of lower bounds on the final demands, i.e., a minimum bill of goods for the region, then by use of the inequality rather than the equality sign, the minimum level of output of industry i is restricted to the sum of its alternative uses, but the possibility that the minimal final demands may be exceeded is not excluded.

The second set of inequalities relates to the water quality standards pertaining to the m pollutants present in the estuarine waters. Given coefficients e_{jp} which indicate the amount of pollutant p expelled per dollar of j's gross output, the total flow of the pollutant into the waters under conditions of no treatment is $e_{jp} X_j$. Thus the second set of inequalities states that the total flow of pollutant p emenating from all n sectors of the economy must not exceed the quality standard S_p established for this pollutant as the maximum computed by the discharge level model noted in Chapter VIII.

$$\sum_{j=1}^{n} e_{jp} X_j \leq S_p \qquad (p = 1, \ldots, m) \quad .$$

Waste treatment considerations are introduced into this basic formulation of the model at a later stage.

OBJECTIVE FUNCTION

Subject to the foregoing three basic constraints, the objective of the program might be to select that combination of outputs and treatment levels that would maximize some measure of regional welfare. With this objective one might choose to maximize an approximate measure of gross regional product $\sum_{j=1}^{n} (v_j X_j)$ where v_j is the value added of sector i.

In a fully employed economy, limitations put on the assimilative capacity of the Bay will result in limitations on the potential growth of the regional economy. Therefore, the objective of the program would be to give rise to those productive sectors with minimum waste contribution while simultaneously satisfying a set of final demands and the established pollutant standards.

In order to set a limit on the output levels of the more productive sectors of the economy, an upper estimate of final demand levels would also be incorporated. The addition of an upper limit Y_i^U would imply that no matter how large a particular industry's relative contribution to regional value added, the industry would not be allowed to produce beyond the reasonable limits of effective demand for its product. Such an upper bound on each sector would of course reflect the capacity constraints of these sectors.

$$Y_i^L \leq X_i - \sum_{j=1}^{n} a_{ij} X_j \leq Y_i^U \qquad (i = 1, \ldots, n) \quad .$$

Thus the basic version of the programming model focuses upon output restrictions as a result of maximum allowable levels of waste discharge to satisfy the quality standard of the Bay.

The program is thus to:

Maximize

$$Z = \sum_{j=1}^{n} v_j X_j$$

Subject to

$$Y_i^U \geq \sum_{j=1}^{n} (\delta_{ij} - a_{ij}) X_j \geq Y_i^L \qquad (i = 1, \ldots, n)$$

$$\sum_{j=1}^{n} e_{jp} X_j \leq S_p \qquad (p = 1, \ldots, m)$$

$$\sum_{j=1}^{n} k_j X_j \leq W$$

$$X_j \geq 0$$

or in matrix notation,

Maximize $$Z = v X$$

Subject to $$Y^U (I - A) x \geq Y^L \qquad (i = 1, \ldots, n)$$

$$e_p X \leq S_p \qquad (p = 1, \ldots, m)$$

$$k X \leq W$$

$$X \geq 0$$

where

$[a_{ij}]$ = matrix of technical coefficients a_{ij} which represent the amount of production from industry i required to support one dollar of output at industry j (\$/time/\$/time) (dimension n x n),

X_j = a vector of gross output of industry j (\$/time)(dimension n),

Y_i = a vector of final demand for output of industry (\$/time) (dimension n),

Y_i^U = upper bound to final demand,

Y_i^L = lower bound to final demand,

s_p = a vector of maximum allowable amount of pollutant p discharged into the estuary (pollutant weight/time) (dimension m),

$[e_{jp}]$ = a matrix of amount of effluent component or pollutant p produced per unit of gross output (pollutant weight/\$) (dimension n x m),

v_j = a vector of value added coefficients (\$/\$/time) (dimension n),

k_j = a vector of effluent produced per unit of gross output (effluent volume/time/\$/time) (dimension n),

W = maximum allowable amount of total effluent to be discharged into the Bay (effluent volume/time) (dimension 1),

$[\delta_{ij}]$ = Kronecker delta (identity matrix).

As discussed in the preceding section, once the formulation of the primal problem has been undertaken, the formulation of the dual problem can be undertaken as well. It should be recalled that there exists as many dual variables or shadow prices as there are constraints in the primal. These prices reflect real opportunity costs and are of considerable value in the economic analysis of the programming problem. While the primal problem can be regarded generally as an allocation problem, the dual can be considered as a pricing problem. The relation between the primal and its dual conforms to the relation between the system of allocation of limited resources to the system of their pricing or imputed values. The dual minimization problem as related to the above primal will be formulated as follows:

Minimize
$$D = \sum_{i=1}^{n} \left(\pi_i^U - \pi_i^L \right) Y_i + \sum_{p=1}^{m} \gamma_p S_p + \rho W$$

Subject to
$$\sum_{i=1}^{n} \left(\pi_i^U - \pi_i^L \right)\left(\delta_{ij} - a_{ij} \right) + \sum_{p=1}^{m} \gamma_p e_{jp} + \rho k_j \geq v_j$$

or in matrix notation,

Minimize
$$D = \left(\pi^U - \pi^L \right) Y + \gamma S + \rho W$$

Subject to
$$\left(\pi^U - \pi^L \right) (I - A) + \gamma e + \rho k \geq v$$

where

π = the vector of "shadow prices" associated with the final constraints. They represent the marginal increase in the objective function due to unit change in the level of final demand.

π^U = is the vector of "shadow prices" associated with the upper bound constraints on final demand ($\pi^U \leq 0$).

π^L = is the vector of "shadow prices" associated with the lower bound constraints on final demand (\$/time)(dimension n) ($\pi^L \geq 0$).

γ = the vector of "shadow prices" associated with the maximum discharge level of pollutants and thus these prices represent the marginal change in the objective function due to a unit change in the allowable discharge levels. Thus they may be considered to be the imputed value to the treatment process, i.e., the opportunity costs of removing a unit of the constituent through treatment (\$/pollutant weight) (dimension m) ($\gamma \leq 0$).

ρ = a scalar; the "shadow price" associated with the maximum discharge level of effluent (\$/volume of effluent) ($\rho \leq 0$).

Thus the dual problem may be interpreted as a problem of minimizing the sum of the imputed value of delivering a required amount to final demand and the imputed values of treatment subject to a constraint which states that the accounting cost of treatment for each sector minus the accounting value of exceeding the lower bound of final demand (or plus the accounting value of not exceeding the upper bound of final demand) should be greater or equal to the value added of this sector.

THE UNTREATED EFFLUENT PROGRAMMING MODEL

Primal Variables, Optimal Solutions, and Infeasible Solutions

The basic programming model as formulated in the preceding section may actually be described as an untreated effluent programming model. Results of such models, i.e., the level of the primal and dual variables, will reflect the effect of the waste discharge constraints on the growth of the economy in general, and on the growth of the various sectors in particular. In contrast to the pollution multiplier model discussed in Chapter IX, which forecasts the critical time periods under assumption of an uncontrolled nonefficient growth pattern of the regional economy, the untreated effluent programming model in which still no treatment is assumed will result in an efficient growth pattern which will maximize the gross regional product and satisfy the projected requirements of deliveries to final demand as well as the water quality constraints. This growth pattern will be followed until the solution to the model becomes infeasible, i.e., again forecasting a critical period in time at which the quality standards with respect to a certain pollutant will be violated unless treatment processes are employed. Since the solution to the programming model represents a growth of a controlled economy, it may be expected that these critical time periods will occur at a later stage than in the uncontrolled economy as expressed by the pollutant multiplier model. Thus restrictions on the growth of certain sectors may postpone the critical time period when the quality standards will be violated without the employment of treatment. The levels of the sectoral outputs are the values of the primal variables at an optimal solution to the programming model.

Empirical Aspects of the Input Data

The untreated effluent programming model as formulated requires the following input data for empirical application:

1. An input-output table of the San Francisco Bay Area (9 counties) of 14 aggregated sectors as developed in Chapter VI.
2. A set of industrial waste load coefficients for 7 types of constituents, the production, as polluting weight per unit of output as developed in Chapter VII.
3. A vector of effluent coefficients specifying the level of effluent for each sector per unit of output.
4. Projections of final demand requirements throughout the period 1963-1980 under assumptions of 3 percent and 6 percent annual growth. These vectors will serve, respectively, as lower and upper bounds on the final demand requirements. The final demand data for selected years are given in Tables VII and VIII.
5. In this model it is assumed that the quality of water in the Bay is expressed by the resulting concentration of certain polluting constituents such as BOD, nitrogen, phosphates, TSS, phenol, etc.,

which are discharged into the Bay. The transformation of maximum allowable concentration levels into maximum allowable discharge levels has been done using the Multicomponent Optimal Quality Control Model [4], as described in Chapter VIII.

From these maximum discharge levels, time dependent amounts of polluting constituents which are expected to exist in domestic effluent and natural runoff as given in Table XVIII are subtracted to result in the right-hand side values to the pollution constraints of the model as given in Table XXIX.

Calculation of future domestic levels of pollutants as given in Table XXVIII is based on population projections as given in Table II, projections of domestic waste load coefficients as given in Table XXX, and on the current levels of treatment of domestic effluent at which 60 percent of the total volume is being treated by primary process while 35 percent is treated by primary and secondary processes. It is also assumed that the percent of secondary treatment of the domestic effluent will increase in the future to at least reach 50 percent of the total volume. The forecasted amounts of pollutants from domestic effluent with three different levels of primary and secondary treatment are given in Table XXXI.

These values of right-hand side for the pollution constraints were calculated for two alternative flow regimes from the Delta into the Bay for flushing purposes — Alternative A — no flushing; Alternative B — with flushing of 2,000 cfs from the Delta which will result in relaxing the minimum quality standards by 25 percent (the annual flushing volume adds 25 percent of fresh water to the average volume of the Bay); i.e., the allowable amounts to be discharged will be 125 percent of the amounts in Alternative A.

6. The volume of effluent allowable to be discharged into the Bay as derived in Chapter VIII.

7. A vector of value added coefficients as given in the table of direct coefficients of the I/O model of the Bay — Table V.

Once these data were derived and introduced into the programming model, a linear programming computer program IBM MPS/360 was employed to arrive at the optimal solutions of the various alternatives as shown by the accompanying format.

Results of the Untreated Effluent Programming Model

Primal Problem. The results of the optimal solution to the primal problem of the programming model may be analyzed with respect to the following aspects:

1. The value of the time dependent objective function.
2. The level of the primal variables.
3. Critical time periods.
4. The effect of flushing from the Delta on the solution.
5. The expected level of pollutant discharge into the Bay.

The numerical results of these items are given in Tables XXXII and XXXIII.

TABLE XXVIII

LEVELS OF UNTREATED DOMESTIC WASTE

Pollutant / Year	1965	1970	1975	1980	1990	2000
Effluent, acre-ft/yr	291,379	332,169	372,960	513,817	602,051	690,352
BOD, ton/yr	121,711	138,750	155,788	213,497	259,019	348,149
TSS, ton/yr	71,544	81,559	91,575	121,990	148,000	203,109
Nitrogen, ton/yr	30,785	35,095	39,405	51,850	62,905	85,565
Phosphates, ton/yr	563	642	721	985	1,195	1,757
Oil and Grease, ton/yr	17,907	20,414	22,921	25,432	30,855	36,282
Gross Heavy Metals[a], ton/yr	260	296	333	369	448	527

[a] Includes floatable materials.

TABLE XVII

PROCEDURE OF CALCULATIONS OF RIGHT-HAND SIDE VALUES FOR THE WATER QUALITY MANAGEMENT PROGRAMMING MODEL

Year		BOD		Nitrogen		Phosphate		Oil and Grease		TDS		Phenol		Gross Heavy Metals		Effluent	
		Mean Volume tons/yr	1.25 x M.V. tons/yr	Mean Volume tons/yr	1.25 x M.V. tons/yr	Mean Volume tons/yr	1.25 x M.V. tons/yr	Mean Volume tons/yr	1.25 x M.V. tons/yr	Mean Volume tons/yr	1.25 x M.V. tons/yr	Mean Volume tons/yr	1.25 x M.V. tons/yr	Mean Volume tons/yr	1.25 x M.V. tons/yr	Mean Volume ac-ft/yr	1.25 x M.V. acre-ft/yr
1965	Criteria	[illegible]	[illegible]	59,395	[illegible]	[illegible]	1,500	[illegible]	[illegible]	190,000	[illegible]	300	378	5,300	6,600	745,000	930,000
	Domestic	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5,750	5,750	21,400	21,400	-	-	100	100	145,000	145,000
	Runoff	[illegible]	5,000	3,500	3,500	110	110	-	-	750	750	-	-	-	-	-	-
	Indust.	[illegible]	[illegible]	27,300	[illegible]	[illegible]	570	[illegible]	[illegible]	117,000	117,000	390	390	780	780	512,000	512,000
	R.H.S.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13,750	[illegible]	53,840	98,843	-	-	4,420	5,720	88,000	275,000
1970	Criteria	[illegible]	[illegible]	59,395	75,467	[illegible]	1,500	31,800	39,800	190,000	235,000	300	378	5,300	6,600	745,000	930,000
	Domestic	[illegible]	[illegible]	34,000	34,000	[illegible]	[illegible]	6,400	6,400	24,500	24,500	-	-	115	115	165,000	165,000
	Runoff	5,000	5,000	3,500	3,500	110	110	-	-	750	750	-	-	-	-	-	-
	R.H.S.	51,383	84,339	[illegible]	40,395	520	808	25,400	33,400	164,800	210,800	300	378	5,185	6,485	580,000	765,000
1975	Criteria	[illegible]	[illegible]	59,395	75,467	1,273	1,580	31,800	39,800	190,000	235,000	300	378	5,300	6,600	745,000	930,000
	Domestic	[illegible]	[illegible]	27,000	27,000	[illegible]	721	7,500	7,500	27,400	27,400	-	-	130	130	185,000	185,000
	Runoff	5,000	5,000	3,500	3,500	110	110	-	-	750	750	-	-	-	-	-	-
	R.H.S.	[illegible]	[illegible]	29,395	45,395	[illegible]	759	24,300	[illegible]	161,900	209,900	300	378	5,170	6,470	560,000	745,000
1980	Criteria	[illegible]	[illegible]	59,395	75,467	1,273	1,590	31,800	39,800	190,000	235,000	300	378	5,300	6,600	745,000	930,000
	Domestic	[illegible]	[illegible]	34,000	34,000	[illegible]	985	5,100	5,100	30,500	30,500	-	-	144	144	205,000	205,000
	Runoff	5,000	5,000	3,500	3,500	113	113	-	-	750	750	-	-	-	-	-	-
	R.H.S.	[illegible]	[illegible]	[illegible]	39,395	[illegible]	485	[illegible]	34,700	158,800	[illegible]	300	378	5,156	6,456	540,000	725,000
1985	Criteria	[illegible]	[illegible]	59,395	75,467	1,273	1,589	59,395	75,467	359,300	457,000	300	378	5,300	6,600	745,000	930,000
	Domestic	[illegible]	[illegible]	48,000	48,000	1,195	1,195	9,800	9,800	[illegible]	57,300	-	-	150	150	250,000	250,000
	Runoff	[illegible]	[illegible]	3,500	3,500	110	110		-	750	750	-	-	-	-	-	-
	R.H.S.	[illegible]	[illegible]	14,395	25,395	-	75	53,395	[illegible]	[illegible]	417,040	[illegible]	378	5,144	6,144	495,000	685,000

TABLE XXX

PROJECTION OF DOMESTIC WASTE LOAD COEFFICIENTS[a]

Year		BOD	Nitrogen	Phosphate	TSS	Oil and Grease	Gross Heavy Metals
1965	Domestic Waste Load						
	lb/capita/day	0.17	0.043	0.008	0.10	0.025	0.004
	ton/10^3 pop./yr	28.07	7.10	0.13	16.5	4.13	0.06
1980-1990	Domestic Waste Load						
	lb/capita/day	0.21	0.051	0.010	0.12	0.025	0.004
	ton/10^3 pop./yr	34.67	8.42	0.16	19.81	4.13	0.06
2000	Domestic Waste Load						
	lb/capita/day	0.24	0.059	0.012	0.14	0.025	0.004
	ton/10^3 pop./yr	39.63	9.74	0.20	23.12	4.13	0.06

[a] See Reference [10].

TABLE XXXI

DOMESTIC EFFLUENT DISCHARGED INTO THE SAN FRANCISCO BAY UNDER VARIOUS COMBINATIONS OF LEVELS OF PRIMARY AND SECONDARY TREATMENT[a]

Constituent	Level of Treatment % of Total Effluent		Domestic Pollutants Discharged (tons/yr)				
	Primary	Secondary	1965	1970	1975	1980	1990
BOD	60	35	59,638	67,987	76,330	104,613	
	75	50	51,118	58,275	65,430	89,668	108,787
	90	65	40,164	45,787	51,410	70,454	85,476
TSS	60	35	21,463	24,467	27,472	36,591	
	75	50	17,886	20,389	22,893	30,497	37,000
	90	65	15,739	17,930	20,130	26,840	32,560
Nitrogen	60	35	27,552	31,410	35,267	46,405	56,299
	75	50	26,167	29,838	33,494	44,072	53,469
	90	65	24,462	28,076	31,524	41,480	50,324
Gross Heavy Metals	60	35	101	115	130	144	175
	75	50	91	103	116	129	156
	90	65	83	95	106	118	143
	60	35	503	574	645	881	1,069
	75	50	478	545	612	837	1,015
	90	65	450	513	577	788	956

[a] Treatment Efficiencies – Percent Removal (see Reference [10]).

Treatment	BOD	Nitrogen	Phosphates	TSS	Gross Heavy Metals
Primary	25-35			60-70	50-60
Secondary	85-95	30-40	30-40	85-95	75-85

FORMAT OF UNTREATED EFFLUENT LINEAR PROGRAMMING MODEL

```
                                         R
                                       F A F F
                           X X X X X   D N D D F F F
         X X X X X X X X X 1 1 1 1 1 F 1 G 2 3 D D D
         1 2 3 4 5 6 7 8 9 0 1 2 3 4 D 1 E 2 3 1 2 3
R1    N  * * * * * * * * * * * * * *
R2    G  *  -*-*  -*  -*  -*-*-*-*-* * * * * * * * *
R3    G -* *-*-*-*-*-*-*-*-*-*-*-*-* * * * * * * * *
R4    G -*-* *-*-*-*-*-*-*-*-*-*-*-* * * * * * * * *
R5    G -*  -* *-*-*-*-*-*-*-*-*-*-* * * * * * * * *
R6    G -*-*-*-* *-*-*-*-*-*-*-*-*-* * * 1 * * * * *
R7    G -*-*-*-*-* *-*-*-*-*-*-*-*-* * * * * * * * *
R8    G -*-*-*-*-*-* *-*-*-*-*-*-*-* * * * * * * * *
R9    G -*-*-*-*-*-*-* *-*-*-*-*-*-* * * 1 * * * * *
R10   G -*-*-*-*-*-*-*-* *-*-*-*-*-* * * * * * * * *
R11   G -*-*-*-*-*-*-*-*-* *-*-*-*-* * * * * * * * *
R12   G -*-*-*-*-*-*-*-*-*-* *-*-*-* * * * * * * * *
R13   G -*-*-*-*-*-*-*-*-*-*-* *-*-* * * * * * * * *
R14   G -*-*-*-*-*-*-*-*-*-*-*-* *-* * * * * * * * *
R15   G -*-*-*-*-*-*-*-*-*-*-*-*-* * * * * * * * * *
R16   L        * * * * * *           * *   * * * * *
R17   L  *     * * * * * * *         * *   * * * * *
R18   L        * * * *     *         * *   * * * * *
R19   L        *   * * *             * *   * * * * *
R20   L        * * * * *   *         * *   * * * * *
R21   L            * * *             * *   * * * * *
R22   L            * *               * *   * * * * *
R23   L  *     * * * * * * *         * *   * * * * *
```

TABLE XXVI

RESULTS OF INTEGRATED EFFLUENT PROGRAMMING MODEL

Year	Contribution of Delta[a]	Gross Regional Product $10^6	Constituents	BOD	Nitrogen	Phosphorus	Oil and Grease	TDS	Phenol	Gross Heavy Metals	Total Effluent (acre-ft)
1965		15,[illegible].57	Allowable Level[b] tons/yr	59,300.00	36,595.00	597.00	9,050.00	336,840.00	459.00	5,200.00	600,000.00
			Actual Level of Discharge tons/yr	[illegible],177.40	18,755.80	574.00	5,738.55	186,871.45	247.95	1,947.76	178,989.46
			Shadow Price $10^3/ton	-	-	-	-	-	-	-	-
1970		[illegible].574.[illegible]	Allowable Level[b] tons/yr	51,040.00	33,595.00	918.00	25,400.00	329,660.00	362.28	5,135.00	580,000.00
			Actual Level of Discharge tons/yr	51,040.00	20,331.58	802.95	8,165.08	272,546.00	362.28	2,855.87	257,492.77
			Shadow Price $10^3/ton	70.70	-	-	-	-	297.62	-	-
	+	22,458.99	Allowable Level[b] tons/yr	64,040.00	49,095.00	828.00	33,400.00	411,000.00	400.00	6,485.00	765,000.00
			Actual Level of Discharge tons/yr	56,575.35	24,739.75	828.00	8,452.41	258,081.00	361.83	2,769.24	258,509.08
			Shadow Price $10^3/ton	-	-	4,085.29	-	-	-	-	-
1975		29,712.05	Allowable Level[b] tons/yr	60,000.00	30,595.00	1,039.00	24,500.00	323,800.00	475.09	5,170.00	560,000.00
			Actual Level of Discharge tons/yr	60,000.00	30,595.00	1,009.70	9,422.80	323,800.00	475.09	3,489.02	312,238.32
			Shadow Price $10^3/ton	51.13	25.02	-	-	4.26	155.20	-	-
	+	29,814.44	Allowable Level[b] tons/yr	75,000.00	45,095.00	1,000.00	32,500.00	404,000.00	500.00	6,470.00	745,000.00
			Actual Level of Discharge tons/yr	63,006.50	32,526.19	1,000.00	9,624.55	294,778.54	469.88	2,950.48	307,143.28
			Shadow Price $10^3/ton	-	-	8,446.52	-	-	-	-	-
1980		[illegible],184.48	Allowable Level[b] tons/yr	65,000.00	32,471.43	1,275.00	24,700.00	327,100.00	475.48	5,156.00	540,000.00
			Actual Level of Discharge tons/yr	65,000.00	32,471.45	1,065.94	9,732.41	326,948.43	475.48	3,307.80	314,452.29
			Shadow Price $10^3/ton	861.51	[illegible].27	-	-	-	24,792.00	-	-
	+	[illegible],478.42	Allowable Level[b] tons/yr	70,000.00	32,440.00	1,275.00	31,700.00	417,000.00	480.00	6,450.00	725,000.00
			Actual Level of Discharge tons/yr	[illegible]	[illegible]	[illegible]	9,919.17	417,000.00	444.35	3,419.41	326,287.20
			Shadow Price $10^3/ton	-	-	-	-	348.17	-	-	-

[a] Plus (+) indicates Alternative 2 – with flushing from Delta.

[b] Some figures are adjusted upwards to arrive at a [illegible] solution.

TABLE XXXIII

OPTIMAL ACTIVITY LEVELS – PRIMAL VARIABLES SOLUTION TO THE UNTREATED EFFLUENT PROGRAMMING MODEL

Year	1963	1970		1975		1980	
Gross Regional Product $\$10^6$	15,496.57	22,576.06	22,658.00	29,712.05	29,814.44	33,184.48	35,676.42
Output $\$10^6$		Without Flushing	With Flushing	Without Flushing	With Flushing	Without Flushing	With Flushing
Sectors							
1	548.34	771.23	799.34	895.13	971.65	954.23	963.06
2	82.73	122.02	118.24	150.65	132.77	144.08	153.57
3	3,553.10	5,202.13	5,204.20	6,989.44	6,992.42	6,126.19	7,966.98
4	3,138.29	4,363.85	4,606.88	4,764.13	5,303.49	5,232.58	5,250.67
5	335.29	476.40	480.93	606.73	614.91	638.15	669.58
6	581.85	849.97	849.38	1,115.86	1,105.64	1,048.97	1,116.92
7	1,635.53	2,423.99	2,324.00	2,925.30	2,464.05	2,773.91	2,865.55
8	303.08	440.73	442.48	582.79	585.91	535.63	646.91
9	679.89	985.49	990.10	1,291.22	1,297.14	1,269.85	1,360.29
10	5,227.94	7,651.19	7,659.56	10,241.45	10,253.83	9,478.83	9,855.45
11	2,897.67	4,229.05	4,237.18	5,583.36	5,579.89	5,364.28	7,013.36
12	3,620.68	5,293.08	5,303.07	7,065.98	7,084.12	8,831.06	9,064.79
13	4,245.52	6,206.43	6,210.92	8,311.71	8,315.23	10,750.67	10,889.89
14	5,040.20	7,350.19	7,366.72	9,782.06	9,807.49	12,274.71	12,605.05

It is clear from these results that while a gradual increase in the gross regional product is expected to take place throughout the planning horizon of the model, the effect of Delta inflow to the Bay remains small, at least until 1980 when the difference in the values of GRP of the two alternatives starts to increase. The small effect of the flushing of the Bay is probably due to the fact that a low growth rate of 6 percent was specified as the upper bound on the growth of final demand, thus having for most sectors in most of the analyzed time periods in both alternatives an optimal solution which satisfies these upper bounds. With a higher expected growth rate, the differences between the two alternatives probably would be greater.

This conclusion is also valid for the values of the primal variables – the optimum sectoral outputs. Yet due to flushing effect, a slight variation in the distribution of sectoral outputs is realized and thus for a few sectors the optimal output without flushing from the Delta may be slightly higher at the expense of those heavy polluting sectors whose output drops to a considerable extent (especially sectors 6 and 7).

While the critical time periods as presented in Table XXXIV can be observed for those constituents which result in shadow prices at a certain time in the future, i.e., the allowable amount to be discharged is exhausted, it is appropriate to remark that for some constituents at certain future years, an infeasible solution resulted from the specified right-hand side levels. To overcome these problems an upward adjustment was made so as to arrive at optimal feasible solution for the whole planning horizon. Thus the results as presented incorporate some violations of the quality standards set up in the preceding chapters. The extent of these violations can be evaluated by comparing the actual amounts of each type of pollutant discharged, as given in Table XXXII, with the original allowable levels of discharge as derived in this chapter and presented in Table XXIX.

Thus the primal solution to the untreated effluent programming model points out the necessity of immediately undertaking treatment of the industrial waste in order to maintain the quality standards set up for the Bay. The argument for extensive treatment will be strengthened by the analysis of the dual problem of the model which reveals the pricing aspects of potential treatment procedure.

The Dual Problem – Shadow Prices. Theoretically there may be three sets of dual variables in an optimal solution to the programming problem, as presented in a preceding section – π, γ, ρ. Yet, while the dual feasibility of the linear programming problems has to be satisified by the nonnegativity of these variables, usually only one of the resources contraints in the primal problem will be tight and thus only one dual variable will be at positive level. This positive level is a result of all the interrelationships of the specified problem and its related data and thus its economic interpretation has to be considered within the frame of the problem solved. Thus a shadow price for BOD in 1975 of 51.13 $/ton as given in Table XXXII has to be considered with all other data and results of the problem and is meaningful only with all the specified constraints.

With this remark in mind it is possible to interpret the dual variable γ as that marginal change in the objective function with a change of unit in the resource. This can be done by partially differentiating the objective function of the dual with respect to the allowable levels of discharge:

$$\frac{\partial D}{\partial S} = \gamma \qquad \text{\$/tons of pollutant}$$

and

$$\frac{\partial D}{\partial W} = \rho \qquad \text{\$/acre-ft of effluent} \quad .$$

TABLE XXXIV

CRITICAL TIME PERIODS RESULTING FROM UNTREATED EFFLUENT – PROGRAMMING MODEL

Constituents / Alternative	BOD	Nitrogen	Phosphates	Oil and Grease	TSS	Phenol	Gross Heavy Metals	Effluent
A - Without Flushing	1973	1975	1965-67	-	1980	1968	-	-
B - With Flushing	-	-	1967-70	-	-	1970	-	-

The resulting shadow prices can be interpreted as the accounting price of treatment. Thus comparing the shadow prices given in Table XXXV for some of the limiting constituents with current costs of treatment processes, it is obvious that the value of treatment to the regional economy is much higher than the actual costs as shown in Table XXXV.

MULTIPHASE TREATMENT PROGRAMMING MODELS

Formulation of the Programming Models

Because the results of the preceding programming model lead to the conclusion that treatment of industrial and domestic waste is essential to satisfy the water quality standards of the Bay, an extension of the basic programming model was formulated which incorporated the various treatment aspects of industrial waste.

Since each industry may have available to it several treatment processes, each with different unit costs, or at least the various processes can be aggregated into three major categories – primary, secondary, and tertiary treatment – the modified treatment model has to account for the possibility of adoption of several treatment phases.

Thus assuming there are h_j processes available to industry j, the basic model may be restated as one whose objective is still the same as before, i.e., to maximize gross regional product net of treatment costs:

$$\text{Maximize} \quad \sum_{j=1}^{n} \left(V_j X_j - \sum_{h=1}^{h_j} C_{jh} W_{jh} \right)$$

subject to the economic growth constraints

$$Y_i^U \geq \sum_{j=1}^{n} \left(\delta_{ij} - a_{ij} \right) X_j \geq Y_i^L \qquad (i = 1, \ldots, n)$$

and the water quality constraints

$$\sum_{j=1}^{n} \left(e_{jp} X_j - \sum_{h=1}^{h_j} g_{jph} W_{jh} \right) \leq S_p \qquad (p = 1, \ldots, m)$$

$$\left[\begin{array}{c}\text{Total Amount of}\\ \text{Pollutant p}\\ \text{from all}\\ \text{Sectors j}\end{array}\right] - \left[\begin{array}{c}\text{Total Amount of}\\ \text{Pollutant p}\\ \text{Removed by all}\\ \text{Treatment}\\ \text{Process } h_j \text{ of}\\ \text{all Sectors j}\end{array}\right] \leq \left[\begin{array}{c}\text{Allowable Amount}\\ \text{of Pollutant}\\ \text{p to be}\\ \text{Discharged}\\ \text{into Bay}\end{array}\right]$$

$$\frac{\text{tons}}{\$10^6} \times \$10^6 \quad - \quad \frac{\text{tons}}{\text{acre-ft}} \times \text{acre-ft} \quad \leq \quad \text{tons}$$

TABLE XXXV

COMPARISON OF SHADOW PRICES FOR TREATMENT OF POLLUTANT WITH ACTUAL TREATMENT COSTS

Constituent →	BOD			Nitrogen			Phosphates			Phenol			TSS		
Shadow Price, 10^3 x $/ton →	50 – 70			25			4,300 – 8,600			400 – 34,800			4 – 348		
Sector	Unit Cost of Treatment (dollars per ton)														
	Pri-mary	Secon-dary	Terti-ary	Pri-mary	Secon-dary	Terti-ary	Pri-mary	Secon-dary	Terti-ary	Pri-mary	Secon-dary	Terti-ary	Pri-mary	Secon-dary	Terti-ary
Agriculture 1	-	-	-	-	230	364	-	-	-	-	-	-	-	-	-
Food 4	37	75	119	-	565	900	-	12,000	19,000	-	-	-	16	34	53
Paper 5	100	204	324	-	8,000	12,700	-	8,100	13,000	-	-	-	640	1,300	2,070
Petroleum 6	100	204	324	-	360	575	-	31,000	49,200	-	3,100[a]	4,900[a]	118	240	380
Stone 7	260	530	840	-	49,500	79,000	-	-	-	-	1.5 x 10^6	2.36 x 10^6	48	99	157
Chemicals 8	820	1,680	2,630	-	2,900	4,600	-	87,200	43,000	-	1.1 x 10^6	1.74 x 10^6	14	28	45
Fabricated Metals 9	2,020	3,840	6,100	-	3,400	5,400	-	-	-	-	-	-	-	-	-
All Others 10	-	-	-	-	1,310	2,080	-	6,600	10,400	-	-	-	52	107	169
Domestic	77	158	251	-	636	1,010	-	34,486	54,772	-	-	-	132	270	428

[a] These figures may be overly conservative since special treatment processes for phenol removal were not considered.

A third set of constraints is added by the logic that the maximum amount of effluent from sector j that will be treated cannot exceed the amount of effluent generated by this sector. It is assumed that this maximum amount of effluent generated by sector j will first be treated by the least-cost treatment process available to the industry which, of course, depends on the pollutant composition of its effluent. The amount of sectoral effluent treated by an advanced phase of treatment with higher unit costs cannot exceed the amount generated by this sector and treated by a lower ranking treatment process; thus

$$W_{jh_f} \leq e_j X_j \qquad \text{for} \quad (j = 1, \ldots, n)$$

$$\text{and} \quad (h_f = \text{the least treatment process available to sector } j)$$

$$W_{jh} \leq W_{jh-1} \qquad (h-1 = \text{the treatment process next to process } h)$$

$$(h = 1, \ldots, h_j)$$

$$X_j \;\; ; \;\; W_{jh} \geq 0$$

where

W_{jh} = amount of effluent from industry j to be treated by process h (effluent volume in acre-ft).

C_{jh} = unit cost of treatment process h to industry j (\$ value/effluent volume in \$/acre-ft).

g_{jph} = amount of pollutant p removed by treatment process h from one unit of industry j's effluent (pollutant weight/effluent volume in tons/acre-ft).

The number of sectors in the above formulation in which two or more treatment processes are adopted will not exceed m [40]. As Carew and Van Slyke have shown [41], the dual of such a multistage model is useful in the evaluation from the regional viewpoint of the adoption of new treatment techniques.

A Model With Natural Runoff and Domestic Waste Water Considerations

Thus far only waste resulting directly from economic activities has been explicitly considered. Additionally, however, estuarine waters customarily receive pollutant flows from natural runoff waters and from discharge of domestic wastes.

The entry into the estuary of a major portion of runoff is through rivers and streams thus making control of this effluent source quite difficult. For these reasons natural runoff is not incorporated into the regional control system explicitly. It is accounted for in the models through reduction of the maximum allowable amount of the pollutant p, S_p, by the amount of the pollutant introduced into the system via this particular source.

Control of natural runoff, as well as other relatively minor sources of pollutants such as sanitary landfill, is likely to be most effectively undertaken through regulations on a local basis.* In the case of the one pollutant from which runoff may be a major source, pesticides, control may have to be instituted on a federal level through restrictions on production and use.

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*For examples of estimations of recreational benefits derived from improved water quality see the articles by J. E. Stevens and by P. Davidson _et al._, see Reference [39].

Domestic waste water flows emanating from sanitary fixtures, garbage disposals, washers, air conditioners, etc. constitute a prime source of some pollutant measures such as BOD (biological oxygen demand) and nitrogen. The inclusion of domestic waste flows within the model can be undertaken through the addition of a domestic sector to the constraints. Letting $\bar{M}_p$ equal the predicted flow pollutant p from domestic waste $\bar{M}$ based primarily upon population estimates, d_{ph}, the amount of pollutant p removed through the treatment process h of one unit of domestic waste, and M_h the amount of domestic effluent to be treated by process h, the water quality constraint becomes

$$\sum_{j=1}^{n}\sum_{p=1}^{m}\left(e_{jp}\,X_j - \sum_{h=1}^{h_j} g_{jph}\,W_{jh} - d_{ph}\,M_h\right) \leq S_p + \bar{M}_p \qquad (p = 1, \ldots, m)$$

$$W_{jh} \leq e_j\,X_j$$

$$M_h \leq \bar{M}$$

(for h = the least cost treatment process available for domestic treatment)

and

$$M_{h-1} \leq M_h$$

and the objective function of this model will thus be

$$\text{Maximize} \quad \sum_{j=1}^{n}\left(V_j\,X_j - \sum_{h=1}^{h_j} C_{jh}\,W_{jh}\right) - \sum_{h=1}^{h_j} C_{dh}\,M_h$$

where C_{dh} is the cost of treating one unit of domestic waste water by process h; and $\bar{M}$ is the total domestic untreated effluent.

Treatment Cost Minimization Models

It has been demonstrated elsewhere [39], in a case study of the Delaware Estuary, that direct and indirect effects on the region's economy resulting from output limitations upon the production of the Paper, Chemical, and Petroleum sectors to maintain the established water quality standards are relatively quite large compared to the additional treatment costs necessary to accomplish the same objectives. In light of these results a model which focuses not upon output restrictions but only upon treatment costs and operations, may be formulated as another version of the two treatment models which will differ only in the objective function which will be the minimization of treatment costs.

The program is thus to

$$\text{Minimize} \quad Z = \sum_{j=1}^{n} \sum_{h=1}^{h_j} c_{jh} W_{jh}$$

subject to the same set of constraints.

With the introduction of domestic effluent this version will be formulated to

$$\text{Minimize} \quad \sum_{j=1}^{n} \sum_{h=1}^{h_j} c_{jh} W_{jh} + \sum_{h=1}^{h_j} c_{dh} M_h \quad ,$$

again subject to the same set of constraints.

Summary of the Four Versions of Multiphase Treatment Models

In light of the foregoing discussion, the multiphase treatment programming model will be employed in the following four versions:

A – Maximization of gross regional product models

(A-1) Without explicit consideration of domestic effluent

Maximize $\quad V X - C W$

Subject to $\quad Y^U \geq (I-A) X \geq Y^L$

$$\left(e_p X - g_p W \right) \leq S_p \qquad (p = 1, \ldots, m)$$

$$W_{jh} \leq e_j X_j \qquad (j = 1, \ldots, n)$$

$$W_{jh} \leq W_{jh-1} \qquad (h = 1, \ldots, h_j)$$

(A-2) With explicit consideration of domestic effluent

Maximize $\quad V X - C W - C_d M$

Subject to $\quad Y^U \geq (I-A) X \geq Y^L$

$$e_p X - g_p W - d_p M \leq S_p + \overline{M}_p \qquad (p = 1, \ldots, m)$$

$$W_{jh} \leq e_j X_j \qquad (j = 1, \ldots, n)$$

(h = least cost treatment process)

$$M_h \leq \overline{M}$$

$$W_{jh} \leq W_{jh-1} \qquad (j = 1, \ldots, n) \quad (h = 1, \ldots, h_j)$$

$$M_{h-1} \leq M_h$$

B — Minimization of multiphase treatment costs

Minimize $C\,W$ (B-1)

Subject to

same constraints as for (A-1) model

Minimize $C\,W + C_d\,M$ (B-2)

Subject to

same constraints as for (A-2) model

Two examples of the formulations of the multiphase treatment programming models are shown on the following pages.

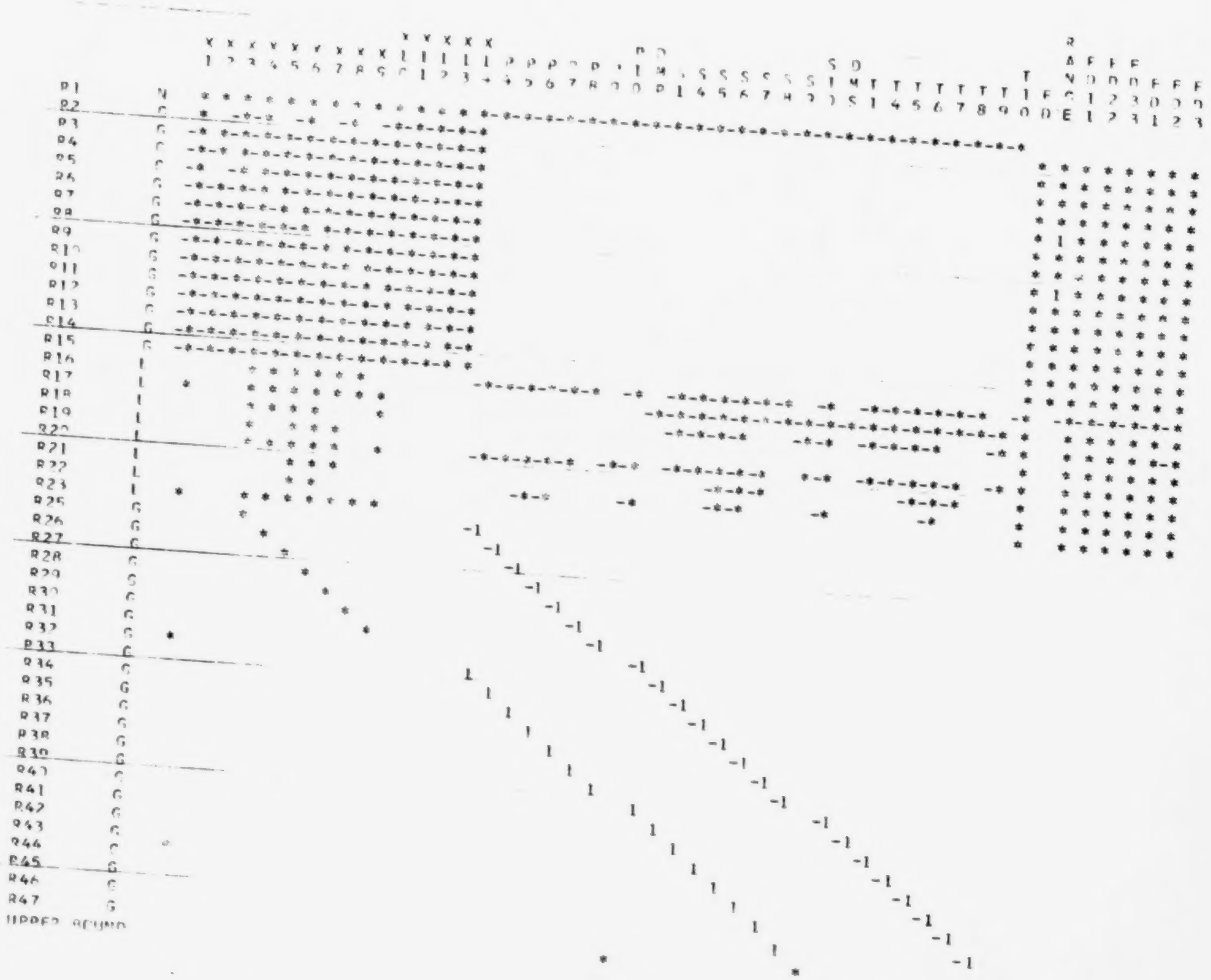
Input Data Aspects

Phases of Treatment — Primary, Secondary, and Tertiary Processes. Treatment techniques for domestic as well as industrial sewage have been largely perfected, and treatment through primary, secondary, and tertiary stages of domestic wastes can render waste water of almost pure quality though each succeeding stage adds to the costs of treatment.

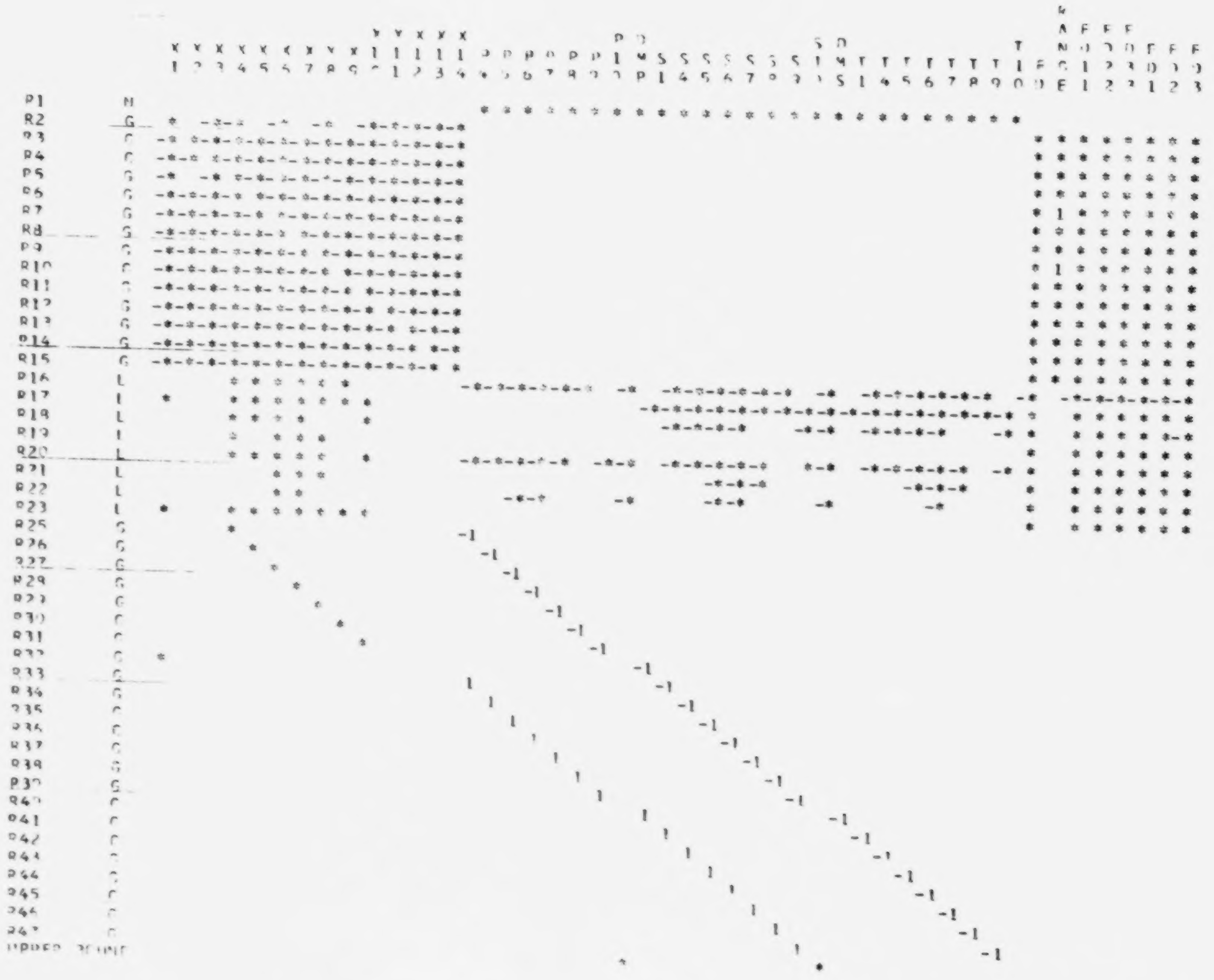
Primary treatment consist of settling raw sewage until the solid material (sludge) is precipitated and the floating particles surface. At this point grease and floating particles are skimmed off and the waste flow that emerges from this process had only one-third of its oxygen-consuming degradable compounds removed.

In secondary treatment, various processes such as chlorination with filtration or activated sludge are used to further decompose wastes. This treatment removes 80 to 90 percent of the BOD in wastes.

FORMAT OF MULTIPHASE TREATMENT PROGRAMMING MODEL - MAXIMIZATION OF GROSS REGIONAL PRODUCT (A-2)



FORMAT OF MULTIPHASE TREATMENT PROGRAMMING MODEL – MINIMIZATION OF TREATMENT COSTS (B-2)


R1 N
R2 G
R3 G
R4 G
R5 G
R6 G
R7 G
R8 G
R9 G
R10 G
R11 G
R12 G
R13 G
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R43 G
R44 G
R45 G
R46 G
R47 G
UPPER BOUND

Tertiary treatment is the last step in achieving almost totally pure water, but it is also an expensive process. At this stage water may be, for example, passed over sand filters and then over activated carbon. Other methods are also available to remove the nondegradable chemicals in the waste waters.

While some industrial wastes differ in their composition from domestic wastes, many can be controlled by the same treatment processes used for domestic wastes as described above. Other wastes (from refineries, for example) may receive a degree of treatment roughly equivalent to secondary treatment.

Thus for the purposes of this model the various treatment processes used for domestic and industrial wastes are defined in terms of these three stages with their corresponding removal efficiencies and unit costs.

Unit Costs and Removal Efficiency. In order to apply the models, data of units costs of each type of treatment process ($/acre-ft) and of removal efficiencies in terms of percentage removal were collected from various sources. Average figures are presented in Tables XXXVI and XXXVII.

TABLE XXXVI

UNIT COSTS OF WASTE WATER TREATMENT[a]

Treatment Process	Size of Plant			
	10[b] mgd		100 mgd	1000 mgd
	Costs			
	$/mil gal	$/acre-ft	$/mil gal	$/mil gal
Primary Treatment				
Conventional	92	31.12	49	38
Advanced	95		51	38
Secondary Treatment				
Activated Sludge, Chlorination with Filtration	201	65.53	104	77
Tertiary Treatment				
Chemical, Filtration, Chlorination, Additional Chemical and Activated Carbon	308		173	124
Activated Sludge, Filtration, Chlorination, Tertiary Chemical and Activated Carbon	336	100.42	189	142
Domestic Wastes[c]				
Primary		12		
Secondary		20		

[a] See Reference [10].

[b] Costs of this plant size were used for calculation in the programming model, thus results can be judged with respect to these conservative estimates.

[c] See Reference [42].

TABLE XXXVII

WASTE WATER TREATMENT PROCESS PERFORMANCE

	Percent Removal						
Constituents Treatment Process	5-day, 20°C BOD[a]	Nitrogen[b]	Phosphates[b]	Suspended Solids[a]	Gross Heavy Metals[a]	Phenol[c]	Oil and Grease[c]
Primary Treatment							
Conventional	25-35			60-70	50-60		
Advanced	40-50			55-65	60-70	50-65	50
Secondary Treatment							
Activated Sludge and Chlorination	85-95	30	30	80-90	75-85		
With Filtration	90-97			85-95	85-95		
Tertiary Treatment							
Chemical, Filtration, Chlorination, Additional Chemical and Activated Carbon	99			99	99		
Activated Sludge, Filtration Chlorination, Tertiary Chemical and Activated Carbon	90-95			99	99		

[a] See Reference [10].

[b] See Reference [27], Table V-3.

[c] See Reference [27], Table IV-12.

Results of the Multiphase Treatment Model for the San Francisco Bay

Primal Problems. In addition to the various aspects of the programming model to be analyzed, as mentioned in the preceding section, a comparison between the results of the four versions of the multiphase programming model is made as well as a comparison with the results of the untreated effluent programming model.

1. A comparison of the optimal values of the objective functions of the two model versions which maximize gross regional product net of treatment cost with the preceding model show very clearly that treatment of industrial and domestic waste to a certain extent is economically efficient and results in higher gross product for the region. The periodical increments to the GRP which result from the various industries operating to their upper limit (satisfying the upper limit of final demand) are larger for the later part of the planning horizon which follows the logic that the limits put on the sectoral growth are more significant as time passes.

   It should also be realized that the actual difference would even be greater as the results of the untreated effluent model incorporate existing violations of the quality standards for the Bay in order to achieve a feasible solution. Thus in order to satisfy even the projected lower growth rate of deliveries to final demand, treatment processes have to be undertaken immediately.

   A summary of the results and comparison is given in Table XXXVIII.

TABLE XXXVIII

GROSS REGIONAL PRODUCT OF THE VARIOUS PROGRAMMING MODELS ($\$10^6$)

	1963	1970		1975		1980	
		With Flushing	Without Flushing	With Flushing	Without Flushing	With Flushing	Without Flushing
Untreated Effluent Model	15,496	22,659	22,576	29,814	29,712	35,676	35,184
Multiphase Treatment Model							
Without Domestic Treatment	15,496	22,699	22,631	30,485	30,398	40,595	40,362
With Domestic Treatment	15,451	22,629	25,569	30,418	29,698	39,773	33,956

The results of the minimum treatment costs models are given in Tables XXXIX and XL. The clear increase in treatment costs when domestic effluent is explicitly considered is not only logic but, as the results of the model indicate, this difference in treatment costs is implicitly absorbed by the domestic "sector" by already assuming a certain level of treatment within this sector in version (A-1).

TABLE XXXIX

MULTIPHASE TREATMENT MODEL - MINIMIZATION OF TREATMENT COSTS
RESULTS OF INDUSTRIAL TREATMENT ONLY

Year	Delta Contribution into Bay	Treatment Costs $\$10^6$	Type of Treatment / Sectors	Effluent to be Treated by Sectors							
				1 acre-ft	4 acre-ft	5 acre-ft	6 acre-ft	7 acre-ft	8 acre-ft	9 acre-ft	10 acre-ft
1963		0	No Treatment	40,000	22,299	29,021	10,796	54,132	6,719	7,169	5,159
1970	With Flushing	0	No Treatment	51,712	27,679	38,055	14,761	79,063	8,484	9,270	6,529
	Without Flushing	35.68	No Treatment	49,200	27,428	35,695	13,279	66,582	8,265	8,818	6,346
			Primary Treatment			12,114					6,346
			Secondary Treatment			12,114					6,346
			Tertiary Treatment			12,114					6,346
1975	With Flushing	10.12	No Treatment	56,998	31,776	41,354	15,385	77,138	9,575	10,216	7,353
			Primary Treatment								5,237
			Secondary Treatment								5,237
			Tertiary Treatment								5,237
	Without Flushing	77.78	No Treatment	56,998	31,776	41,354	15,385	77,138	9,575	10,216	7,352
			Primary Treatment			31,417	1,472				7,352
			Secondary Treatment			31,417	1,472				7,352
			Tertiary Treatment			31,417	1,472				7,352
1980	With Flushing	94.88	No Treatment	66,000	36,794	47,884	17,813	89,301	11,087	11,829	8,513
			Primary Treatment			38,954	1,620				8,513
			Secondary Treatment			38,954	1,620				8,513
			Tertiary Treatment			38,954	1,620				8,513
	Without Flushing	220.11	No Treatment	66,000	36,794	47,884	17,813	89,301	11,087	11,829	8,513
			Primary Treatment		36,794	47,884	3,189	17,489			8,513
			Secondary Treatment		36,794	47,884	3,189	17,489			8,513
			Tertiary Treatment		36,794	47,884	3,189	17,489			8,513

TABLE XI

MULTIPHASE TREATMENT MODEL - MINIMIZATION OF TREATMENT COSTS
RESULTS OF INDUSTRIAL AND DOMESTIC TREATMENT

Year	Delta Contribution into Bay	Treatment Costs $\$10^6$	Type of Treatment / Sectors	Effluent to be Treated by Sectors								
				Domestic acre-ft	1 acre-ft	4 acre-ft	5 acre-ft	6 acre-ft	7 acre-ft	8 acre-ft	9 acre-ft	10 acre-ft
1965		42.7	No Treatment	291,779	40,000	22,299	29,021	10,796	54,132	6,719	7,169	5,159
			Primary Treatment			18,507	3,608					
			Secondary Treatment			18,507	3,608					
			Tertiary Treatment			18,507	3,608					
1970	With Flushing	59.9	No Treatment	332,169	49,200	27,428	35,695	13,279	66,582	8,265	8,818	6,346
			Primary Treatment	11,085		27,428						
			Secondary Treatment	11,085		27,428						
			Tertiary Treatment			27,428						
	Without Flushing	97.6	No Treatment	332,169	49,200	27,428	35,695	13,279	66,582	8,265	8,818	6,346
			Primary Treatment			22,633	27,860					
			Secondary Treatment			22,633	27,860					
			Tertiary Treatment			22,633	27,860					
1975	With Flushing	81.3	No Treatment	372,960	56,998	31,776	41,354	15,385	77,138	9,575	10,216	7,352
			Primary Treatment			28,383	13,675					
			Secondary Treatment			28,383	13,675					
			Tertiary Treatment			28,383	13,675					
	Without Flushing	168.8	No Treatment	372,960	56,998	31,776	41,354	15,385	77,138	9,575	10,216	7,352
			Primary Treatment			31,776	41,354	9,534				2,208
			Secondary Treatment		2,882	31,776	41,354	9,534				2,208
			Tertiary Treatment		2,882	31,776	41,354	9,534				2,208
1980	With Flushing	235.3	No Treatment	513,817	66,000	36,794	47,884	17,814	89,301	11,087	11,829	8,513
			Primary Treatment	166,384		36,794	47,884	17,814	89,301			8,513
			Secondary Treatment	166,384	23,233	36,794	47,884	17,814	89,301			8,513
			Tertiary Treatment		23,233	36,794	47,884	17,814	89,301			8,513
	Without Flushing	528.6	No Treatment	513,817	66,000	36,794	47,884	17,814	89,301	11,087	11,829	8,513
			Primary Treatment			36,794	47,884	16,502				8,513
			Secondary Treatment		14,105	36,794	47,884	16,502				8,513
			Tertiary Treatment		14,105	36,794	47,884	16,502				8,513

2. The value of the flushing water from the Delta at a rate of 2,000 cfs, which is assumed to increase the assimilative capacity of the Bay by 25 percent, can be directly obtained from the difference between the values of minimum treatment costs of the two alternatives as follows:

TABLE XLI

VALUE OF FLUSHING FROM DELTA

	Year		
	1970	1975	1980
Minimum Treatment Costs Without Domestic Effluent			
Without Flushing ($\$10^6$)	35.68	77.78	220.11
With Flushing ($\$10^6$)	0	10.12	94.88
Value of Flushing ($\$10^6$)	35.68	67.66	125.23
Minimum Treatment Costs With Domestic Effluent			
Without Flushing ($\$10^6$)	97.60	168.80	528.60
With Flushing ($\$10^6$)	59.90	81.30	235.30
Value of Flushing ($\$10^6$)	37.70	87.50	293.30

3. In contrast to the first programming model, the primal variables of main interest are those which express the recommended level of treatment processes required by each sector as presented in Tables XLII and XLIII.

   The main features of these results are as follows:

   a. Only a few industries are required to treat their effluent.

   b. The number of industries increases for the later part of the planning horizon.

   c. Some of the industries in some of the time periods which are recommended to treat their effluent are different in the two models (B-1) and (B-2).

   d. Once an industry is expected to treat its effluent the optimal solutions of the models advocates full treatment, i.e., primary, secondary, and tertiary. These types of optimal solutions may be the result of too low unit costs assigned advanced treatment processes although these costs are the average ones given in the literature. Different results may be obtained with a greater range between the various unit costs.

   e. The results of the models which incorporate domestic effluent point out decisively that treatment of industrial waste rather than domestic should be preferred. These conclusions result from both types of models.

TABLE XLII

MULTIPHASE TREATMENT MODEL - MAXIMIZATION OF GROSS REGIONAL PRODUCT
RESULTS OF INDUSTRIAL TREATMENT ONLY

Year	Delta Contribution into Bay	Gross Regional Product $\$10^6$	Sectors Type of Treatment	Effluent to be Treated by Sectors							
				1 acre-ft	4 acre-ft	5 acre-ft	6 acre-ft	7 acre-ft	8 acre-ft	9 acre-ft	10 acre-ft
1963		15,496	No Treatment	41,153	22,784	29,740	11,037	54,725	6,898	7,370	5,280
1970	With Flushing	22,699	No Treatment	60,000	33,449	43,532	16,195	81,197	10,079	10,754	7,740
			Primary Treatment								1,555
			Secondary Treatment								1,555
			Tertiary Treatment								1,555
	Without Flushing	22,631	No Treatment	60,000	33,449	43,532	16,195	81,197	10,079	10,754	7,740
			Primary Treatment			26,817	2,059				7,740
			Secondary Treatment			26,817	2,059				7,740
			Tertiary Treatment			26,817	2,059				7,740
1975	With Flushing	30,485	No Treatment	80,800	45,045	58,622	21,808	109,346	13,574	14,482	10,422
			Primary Treatment			30,079	4,515				10,422
			Secondary Treatment			30,079	4,515				10,422
			Tertiary Treatment			30,079	4,515				10,422
	Without Flushing	30,398	No Treatment	80,800	45,045	58,622	21,808	109,346	13,574	14,482	10,422
			Primary Treatment		9,405	58,622	6,128				10,422
			Secondary Treatment	6,461	9,405	58,622	6,128				10,422
			Tertiary Treatment	6,461	9,405	58,622	6,128				10,422
1980	With Flushing	40,595	No Treatment	108,000	60,208	78,355	29,150	146,139	18,143	19,358	13,931
			Primary Treatment		32,262	78,355	9,836				13,931
			Secondary Treatment	5,441	32,262	78,355	9,836				13,931
			Tertiary Treatment	5,441	32,262	78,355	9,836				13,931
	Without Flushing	40,362	No Treatment	108,000	60,208	78,355	29,150	146,139	18,143	19,358	13,931
			Primary Treatment		60,208	78,355	29,150	55,311			13,931
			Secondary Treatment	26,876	60,208	78,355	29,150	55,311			13,931
			Tertiary Treatment	26,876	60,208	78,355	29,150	55,311			13,931

TABLE XLIII

MULTIPHASE TREATMENT MODEL - MAXIMIZATION OF GROSS REGIONAL PRODUCT
RESULTS OF INDUSTRIAL AND DOMESTIC TREATMENT

Year	Delta Contribution into Bay	Gross Regional Product $\$10^6$	Sectors / Type of Treatment	Effluent to be Treated by Sectors								
				Domestic acre-ft	1 acre-ft	4 acre-ft	5 acre-ft	6 acre-ft	7 acre-ft	8 acre-ft	9 acre-ft	10 acre-ft
1963		15,451	No Treatment	291,379	41,153	22,783	29,740	11,037	54,725	6,898	7,370	5,280
			Primary Treatment			18,421	4,934					
			Secondary Treatment			18,421	4,934					
			Tertiary Treatment			18,421	4,934					
1970	With Flushing	22,629	No Treatment	332,169	60,000	33,448	43,532	16,195	81,197	10,079	10,754	7,740
			Primary Treatment			32,738	4,930					
			Secondary Treatment			32,738	4,930					
			Tertiary Treatment			32,738	4,930					
	Without Flushing	22,569	No Treatment	332,169	60,000	32,449	43,532	16,195	81,197	10,079	10,754	7,740
			Primary Treatment			24,321	34,662	2,059				7,740
			Secondary Treatment		402	24,321	34,662	2,059				
			Tertiary Treatment		402	24,321	34,662	2,059				7,740
1975	With Flushing	30,418	No Treatment	372,960	80,800	45,045	58,622	21,808	109,346	13,574	14,482	10,422
			Primary Treatment			23,365	52,211	4,515				
			Secondary Treatment			23,365	52,211	4,515				
			Tertiary Treatment			23,365	52,211	4,515				
	Without Flushing	29,698	No Treatment	372,960	76,129	41,088	56,727	19,164	82,457	13,387	14,149	10,368
			Primary Treatment			36,148	56,165	4,188				10,368
			Secondary Treatment		27,190	36,148	56,165	4,188				10,368
			Tertiary Treatment		27,190	36,148	56,165	4,188				10,368
1980	With Flushing	39,773	No Treatment	513,817	107,315	59,712	76,705	24,713	98,996	17,984	19,021	13,875
			Primary Treatment			59,712	76,705	24,713	2,009			13,875
			Secondary Treatment		50,570	59,712	76,705	24,713	2,009			13,875
			Tertiary Treatment		50,570	59,712	76,705	24,713	2,009			13,875
	Without Flushing	33,956	No Treatment	513,817	72,159	37,659	60,764	21,067	94,336	12,629	14,634	12,589
			Primary Treatment	145,469		37,659	60,764	21,067	94,336			12,589
			Secondary Treatment	145,469	30,716	37,659	60,764	21,067	94,336			12,589
			Tertiary Treatment		30,716	37,659	60,764	21,067	94,336			12,589

4. In the multiphase treatment models it was not required to make any adjustment to the right-hand side values in order to obtain feasible solutions, thus the levels of untreated effluent to be discharged into the Bay are those which will satisfy the specified quality standards for the various pollutants. These levels are given in Tables XXXIX, XL, XLII, and XLIII as the difference between the amounts of total effluent and the amounts to be treated.

Dual Problems. As in the previous model, dual problems for the primal problems may be formulated and an economic interpretation may be applied to the dual variables, i.e., shadow prices. There are thus n accounting or shadow prices, $\alpha_1, \ldots, \alpha_n$, associated with the initial set of constraints. Variables $\alpha_i = \partial Z/\partial Y_i$ represent the marginal increase in minimum total treatment costs per unit increase in the final demand of industry i. From the nature of the formulation, $\alpha_i \leq 0$ since an increase in the maximum production level of a particular industry which satisfies the upper bounds of final demand will result in an increase of effluent production and may therefore result in greater minimum treatment costs. The α_i are useful in ascertaining the effects upon the minimum treatment cost required to maintain a given quality standard in the face of relatively small changes in the final demands for the outputs of the various regional industries.

There is secondly a set of m accounting prices, $\lambda_1, \ldots, \lambda_m$ $\lambda_p = \partial Z/\partial S_p$ or $\partial Z/\partial(S_p + M_p)$ which indicates the marginal increases in minimum cost resulting from a unit increase in the amount of effluent component p allowed in the estuary. $\lambda_p \leq 0$ since the greater the amount of pollutant p allowed in the estuarine waters, the less the amount that must be subjected to treatment.

The use of the λ_p dual variables may be exemplified through the assignment of values to various levels of augmentation of the estuarine waters such as the flushing from the Delta. Releases into the estuary of large quantities of fresh water from reservoirs are sometimes desirable, not only to remove pollutants discharged into the estuary, but to counteract sea water intrusion through the ocean inlet. If at mean volume v of the waters S_p is the quality standard for pollutant p, then with an augmentation of volume v' the new standard may be represented as $S_p + A_p v'$ where the value of A_p is such as to maintain the maximum allowable concentration ratio.

$$\frac{S_p + A_p v'}{v + v'} = \frac{S_p}{v} \quad .$$

The value of augmentation v' to the regional economy in terms of reduced treatment cost is thus $- A_p v' \lambda_p$. This shadow price of the flushing from the Delta is the value of flushing obtained from the dual problem.

There is lastly a set of n dual variables $\beta_i = \partial Z/\partial k_j X_j \geq 0$ which indicate the increase in treatment costs per unit of additional effluent produced by sector j. However, as earlier discussed, the set of Y_i prescribed from the first set of constraints will precisely determine the set of X_i forthcoming from the regional economy. Thus under the assumption of fixed technical and effluent coefficients, the β_i yield no new information since they can be determined from the values of the α_i.

$$\beta_i = \frac{\partial Z}{\partial k_j X_j} = \frac{\partial Z}{k_j (I-A)^{-1} \partial Y_i} = \frac{\alpha_i}{k_j (I-A)^{-1}} \quad .$$

The shadow prices for the different models for the various time periods are given in Tables XLIV and XLV.

EXTENSIONS

Multiple Quality Standards

If the pattern of withdrawers of, and dischargers into, the estuarine waters and the physical configuration of the waters is such that differing beneficial uses of the waters can be ascribed to various portions of the estuary, it would of course be highly inefficient to prescribe a single quality standard for any pollutant to the entire estuary. Quality intake standards have been shown to vary significantly between industries [43] and as a result widely differing quality standards may be established for various segments of the estuary. This potential variation of standards is accentuated by the possibility that portions or segments of the estuary may be reserved primarily for the promotion of fish life and for recreational uses.

In recommending standards for the San Francisco Bay, the San Francisco Bay-Delta Water Quality Control Program has stated that

> "The uses and the water quality necessary for those uses vary from area to area. Both the uses and the water quality in the Delta are very different from the water quality and associated uses in the central portions of San Francisco Bay. To handle this problem, ten Water Quality Zones were established over the Bay-Delta system to permit differentiation of uses and water quality in different parts of the system. These Zones were determined by the physical configuration of the Bay, or by the nature of the physical, chemical, and biological data available for this study." [10]

Once an estuary has been so apportioned into various segments on the basis of the above criteria, the overall objective of the regional water quality program is to minimize the sum of the treatment costs incurred in each of the estuarine segments. Assuming an estuary divided into L zones or segments and ignoring, for purposes of exposition, domestic waste waters and the possibility of multistage treatments, the objective in terms of our programming model is to

$$\text{Minimize} \sum_{\ell=1}^{L} \sum_{j=1}^{n} {}_{\ell}C_j \; {}_{\ell}W_j \quad .$$

The water quality constraints of the program must now take into consideration the fact that effluent discharge into one segment of the estuary may have, through dispersion, a damaging effect upon the quality of the waters in adjacent segments. We thus introduce into the model the coefficient ${}_{\ell k}z_p$ which represents the amount of pollutant p which appears through dispersive action in segment or zone ℓ. In keeping with the general limitation of the program to linear relationships, the appearance of a pollutant in any one segment through dispersive action is assumed to be a linear function (or a function that can be readily linearly approximated) of the amount discharged into an adjacent segment. The effect upon zone k in terms of a particular pollutant p resulting from economic activity in segment ℓ may now be calculated by applying the new coefficient to the net amount of the pollutant entering the waters of segment ℓ to yield

TABLE XLIV

DUAL VARIABLES (SHADOW PRICES) FOR TREATMENT MODELS WITHOUT FLUSHING ($\$10^6$)

Shadow Price	Year	1970				1975				1980			
	Model	A-1	A-2	B-1	B-2	A-1	A-2	B-1	B-2	A-1	A-2	B-1	B-2
	Row[a]												
α	2	- 0.673	- 0.545	- 0.002	- 0.002	- 0.545	- 0.475	- 0.003	- 0.129	- 0.544	+ 1.312[b]	- 0.005	- 0.132
	3	- 0.795	- 0.794	- 0.001	- 0.001	- 0.794	- 0.779	- 0.001	- 0.001	- 0.794	- 0.403	- 0.002	- 0.002
	4	- 0.808	- 0.807	- 0.003	- 0.003	- 0.807	- 0.774	- 0.004	- 0.004	- 0.807	+ 0.062[b]	- 0.005	- 0.005
	5	- 0.595	- 0.573	- 0.015	- 0.017	- 0.571	-	- 0.015	- 0.030	- 0.570	+ 14.562[b]	- 0.025	- 0.040
	6	- 0.538	- 0.543	- 0.198	- 0.177	- 0.542	- 0.500	- 0.199	- 0.168	- 0.597	+ 0.524[b]	- 0.135	- 0.135
	7	- 0.738	- 0.733	- 0.018	- 0.020	- 0.731	+ 0.060[b]	- 0.044	- 0.045	- 0.727	+ 20.211[b]	- 0.055	- 0.055
	8	- 0.386	- 0.383	- 0.020	- 0.017	- 0.378	+ 0.014[b]	- 0.021	- 0.022	- 0.334	+ 10.166[b]	- 0.072	- 0.072
	9	- 0.660	- 0.659	- 0.008	- 0.009	- 0.660	- 0.621	- 0.009	- 0.011	- 0.661	+ 0.344[b]	- 0.008	- 0.008
	10	- 0.787	- 0.785	- 0.004	- 0.004	- 0.785	- 0.764	- 0.005	- 0.006	- 0.786	- 0.223	- 0.004	- 0.006
	11	- 0.765	- 0.764	- 0.007	- 0.007	- 0.764	- 0.735	- 0.008	- 0.009	- 0.765	- 0.004	- 0.007	- 0.008
	12	- 0.891	- 0.891	- 0.001	- 0.001	- 0.890	- 0.871	- 0.001	- 0.002	- 0.889	- 0.368	- 0.003	- 0.003
	13	- 0.954	- 0.953	- 0.002	- 0.002	- 0.953	- 0.939	- 0.002	- 0.002	- 0.953	- 0.576	- 0.002	- 0.003
	14	- 0.938	- 0.936	- 0.001	- 0.001	- 0.936	- 0.926	- 0.001	- 0.002	- 0.936	- 0.667	- 0.001	- 0.003
	15	- 0.872	- 0.870	- 0.003	- 0.003	- 0.870	- 0.837	- 0.003	- 0.004	- 0.870	-	- 0.004	- 0.005
λ	16		- 0.0001		+ 0.0005		- 0.0001		+ 0.0008				
	17		- 0.005			- 0.005	- 0.005		+ 0.005	- 0.005	- 0.005		+ 0.005
	18	- 0.212	- 0.194	+ 0.212	+ 0.167	- 0.255	- 0.194	+ 0.212	+ 0.164	- 0.758	- 0.803	+ 0.811	+ 0.803
	19						- 0.408				- 10.761	+ 0.010	
	20												
	21	- 0.048	- 0.012			- 0.012	- 0.012	+ 0.048					
	23												

[a] Row 2 corresponds to sector 1, ..., row 15 corresponds to sector 14; rows 16-23 correspond to constituent constraints (BOD, nitrogen, ..., effluent).

[b] Final demand at lower limit.

TABLE XLV

DUAL VARIABLES (SHADOW PRICES) FOR TREATMENT MODELS WITH FLUSHING ($$10^6$)

Shadow Price	Year	1970				1975				1980			
	Model	A-1	A-2	B-1	B-2	A-1	A-2	B-1	B-2	A-1	A-2	B-1	B-2
	Row[a]												
α	2	- 0.673	- 0.673	-	- 0.0008	- 0.673	- 0.673	- 0.002	- 0.002	- 0.545	- 0.474	- 0.003	- 0.131
	3	- 0.795	- 0.795	-	- 0.0004	- 0.795	- 0.795	- 0.001	- 0.001	- 0.794	- 0.779	- 0.001	- 0.002
	4	- 0.809	- 0.809	-	- 0.0015	- 0.808	- 0.809	- 0.003	- 0.003	- 0.807	- 0.774	- 0.004	- 0.005
	5	- 0.597	- 0.594	-	- 0.0033	- 0.595	- 0.593	- 0.013	- 0.016	- 0.571	-	- 0.015	- 0.039
	6	- 0.557	- 0.560	-	- 0.061	- 0.538	- 0.559	- 0.180	- 0.177	- 0.542	- 0.554	- 0.199	- 0.174
	7	- 0.766	- 0.763	-	- 0.015	- 0.738	- 0.742	- 0.017	- 0.020	- 0.731	+ 0.061[b]	- 0.449	- 0.054
	8	- 0.389	- 0.390	-	- 0.003	- 0.386	- 0.389	- 0.018	- 0.017	- 0.378	+ 0.060[b]	- 0.021	- 0.045
	9	- 0.662	- 0.660	-	- 0.008	- 0.660	- 0.659	- 0.007	- 0.009	- 0.660	- 0.623	- 0.009	- 0.009
	10	- 0.788	- 0.788	-	- 0.001	- 0.787	- 0.787	- 0.004	- 0.004	- 0.785	- 0.764	- 0.005	- 0.006
	11	- 0.766	- 0.767	-	- 0.002	- 0.765	- 0.766	- 0.007	- 0.007	- 0.764	- 0.736	- 0.008	- 0.009
	12	- 0.891	- 0.891	-	- 0.0004	- 0.891	- 0.891	- 0.001	- 0.001	- 0.890	- 0.869	- 0.001	- 0.003
	13	- 0.954	- 0.954	-	- 0.0006	- 0.954	- 0.954	- 0.002	- 0.002	- 0.953	- 0.939	- 0.002	- 0.003
	14	- 0.938	- 0.938	-	- 0.0003	- 0.938	- 0.938	- 0.001	- 0.001	- 0.936	- 0.926	- 0.001	- 0.003
	15	- 0.872	- 0.872	-	- 0.001	- 0.872	- 0.872	- 0.003	- 0.003	- 0.870	- 0.838	- 0.003	- 0.005
λ	16		- 0.0005		+ 0.0016		- 0.0005		+ 0.0005				
	17									- 0.005	- 0.005		+ 0.005
	18	- 0.193	- 0.167			- 0.212	- 0.167	+ 0.193	+ 0.167	- 0.255	- 0.758	+ 0.212	+ 0.446
	19	- 0.193									- 0.405		
	20												
	21					- 0.048	- 0.038			- 0.012		+ 0.048	
	22												
	23												

[a] Row 2 corresponds to sector 1, ..., row 15 corresponds to sector 14; rows 16-23 correspond to constituent constraints (BOD, nitrogen, ..., effluent).

[b] Final demand at lower limit.

$$ {}_{\ell k}z_p \sum_{j=1}^{n} (e_{jp}\,{}_{\ell}X_j - g_{jp}\,{}_{\ell}W_j) $$

where the variables X_j appearing in the expression are as previously defined but now set in a spatial context by the subscript ℓ.

The water quality constraints for each zone in the program indicate as before that the amount of pollutant p released after treatment cannot exceed the established standard, and secondly that the amount of effluent treatment in each spatial sector cannot exceed the amount of effluent produced by that sector,

$$ {}_k s_p - \sum_{\ell=1}^{L} [(1 - {}_{k\ell}z_p) \sum_{j=1}^{n} (e_{jp}\,{}_k X_j - g_{jp}\,{}_k W_j) $$

$$ + {}_{k\ell}z_p \sum_{j=1}^{n} (e_{jp}\,{}_{\ell}X_j - g_{jp}\,{}_{\ell}W_j)] \geq 0 $$

$$ (\ell = k) $$
$$ (p = 1, \ldots, m) $$

$$ k_j\,{}_{\ell}X_j - {}_{\ell}W_j \geq 0 $$

$$ (j = 1, \ldots, n) $$
$$ (\ell = 1, \ldots, L) \quad . $$

Once the outputs of each sector have been spatially identified, it is desirable to develop an economic model that is structured in such a manner as to yield information as to the effects throughout the system which will result from changes in the economic demands upon any given industry. The increased production of industry i in zone ℓ may result in a greater amount of effluent in zone k, not only through hydrologic dispersive action but also through economic linkages as well by stimulating or inducing increased output from industry j located in zone k. Multiplier effects such as these can be estimated through the extension of the regional input-output model into an interregional formulation.

Interregional input-output analysis differs from the regional model in that the former attempts to incorporate spatial location. Regional interdependence analysis disaggregates production and consumption totals in terms of commodities or industries; interregional theory likewise breaks down these totals by commodities but also in terms of geographic location. The interregional model concentrates upon the economic relationships not only within each region but among the regions as well. If an industry i in region ℓ requires as an input the product of industry j in region m, a direct economic "tie" or interdependence exists between the two industries and thus the two regions. If industry k in region n then purchases for its production process the product of industry i in region ℓ, in addition to the direct link formed between regions n and ℓ, an indirect tie is established between regions n and m. Interregional input-output theory is designed to reveal both these direct and indirect interdependencies among regions [44].

Identifying each region with a particular estuarine zone, the interregional model enables us to provide the type of analysis needed for the new segmented system.

In our programming model the economic conditions may be restated as

$$\left(I - \sum_{\ell=1}^{L} \sum_{j=1}^{n} {}_{k\ell}a_{ij} \right) {}_{k}X_{j} = {}_{k}Y_{i} \qquad \begin{array}{l} (i = 1, \ldots, n) \\ (k = 1, \ldots, L) \end{array}$$

where ${}_{k\ell}a_{ij}$ is the amount of production of industry i in region k required by industry j in region ℓ for the latter industry to produce one dollar of gross output.

Interzonal Effluent Shipments

Due to the tidal characteristics of estuary waters, almost all pollutants will ultimately be deposited in the ocean. The dilution capabilities due to tidal action will vary significantly, however, between the different estuarine segments. The nearer the disposal site is to the ocean inlet, the more effective will be the tidal flushing action. In the San Francisco estuary, for example, the dilution capabilities of the central portions of the Bay which are adjacent to the connecting passage with the ocean at the Golden Gate, are up to fifty times greater than those of the dispersive actions of the extreme northern estuarine waters.

As an additional extension of the model we might therefore consider the possibility of transporting effluent between zones, now that the model of the estuary has been spatially segmented. As economic activity expands and higher cost treatment processes are necessitated, the possibility of shipping effluent between estuarine segments via pipelines becomes an increasingly viable economic alternative to on-site treatment. Such shipments may be made from zones where quality standards are being approached to other segments where conditions are more favorable to waste disposal. Alternatively, the destination of the waste shipments might be to a regional treatment plant which is designed to take advantage of certain economies of scale by treating the wastes from two or more zones.

Assuming the cost of the effluent shipment to be linearly dependent upon the volume transported, we may let ${}_{\ell k}t_{j}$ represent the total volume of effluent from industry j in zone ℓ to be conveyed to zone k for disposal and ${}_{\ell k}c'_{j}$ the cost of transporting one unit of this effluent. To simplify the exposition let us assume that region k represents the only logical zone to which shipments may be made. The objective of the program then is to minimize the total regional cost of a system of treatment operations and interzonal shipments, i.e., to:

$$\text{Minimize} \quad Z = \sum_{\ell=1}^{L} \sum_{j=1}^{n} \sum_{h=1}^{h_j} {}_{\ell}c_{jh} \, {}_{\ell}W_{jh} + \sum_{\ell=1}^{L} \sum_{j=1}^{n} {}_{\ell k}c'_{j} \, {}_{\ell k}t_{j}$$

and the water constraints may be restated as

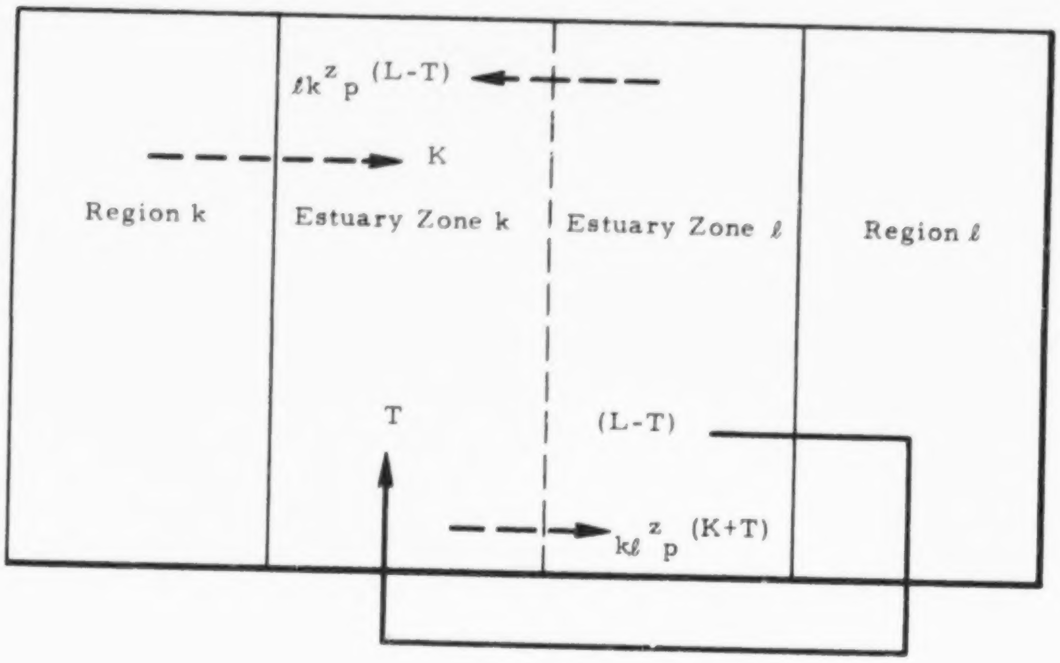
$$e_{jp} \, {}_{\ell}X_{j} - {}_{\ell k}t_{j} - \sum_{h=1}^{h_j} g_{jph} \, {}_{\ell}W_{jh} \geq 0 \qquad \begin{array}{l} (\ell = 1, \ldots, L) \\ (i = 1, \ldots, n) \\ (p = 1, \ldots, m) \end{array}$$

$${}_{\ell k}t_j, \quad {}_{\ell}W_{jh} \geq 0 \text{ for all subscripts } \ell,\ j, \text{ and } h.$$

$$ {}_{k}s_p - \sum_{\ell=1}^{L}{}_{h_j} \left[(1 - {}_{k\ell}z_p) \sum_{j=1}^{n} \left\{ e_{jp} \left({}_{k}X_j + {}_{\ell k}t_j \right) - \sum_{h=1}^{h_j} g_{jph}\, {}_{k}W_{jh} \right\} \right. $$

$$ \left. + {}_{\ell k}z_p \sum_{j=1}^{n} \left\{ e_{jp} \left({}_{\ell}X_j - {}_{\ell k}t_j \right) - \sum_{h=1}^{h_j} g_{jph}\, {}_{\ell}W_{jh} \right\} \right] \geq 0 \qquad \begin{matrix} (\ell = k) \\ (p = 1, \ldots, m) \end{matrix} \quad . $$

Assuming an estuary apportioned into two zones, the above constraint is presented diagramatically for p = 1, ..., m.


$_{\ell k}z_p$ (L-T)
K
Region k
Estuary Zone k
Estuary Zone ℓ
Region ℓ
T
(L-T)
$_{k\ell}z_p$ (K+T)

where

$$ K = \sum_{j=1}^{n} \left(e_{jp}\, {}_{k}X_j - \sum_{h=1}^{h_j} g_{jph}\, {}_{k}W_{jh} \right) $$

$$L = \sum_{j=1}^{n} \left(e_{jp} \, {}_{\ell}X_j - \sum_{h=1}^{h_j} g_{jph} \, {}_{\ell}W_{jh} \right)$$

$$T = \sum_{j=1}^{n} e_{jp} \, {}_{\ell k}t_j \quad .$$

SECTION III

Summary And Conclusions

Phases 1-5

by

P. H. McGauhey

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XI. SUMMARY AND CONCLUSIONS

SUMMARY

Studies of the Economic Evaluation of Water Quality were initiated in 1962 in recognition of the growing percentage of the nation's water resource being degraded in quality through beneficial use; and the ever-increasing investment in waste water treatment works necessary to repair the damage to receiving waters. At that time the question of how water quality criteria established by regulatory agencies for any given sector of the water resource might be achieved at a minimum cost was being asked in many quarters, but the concepts of benefit-cost and pollution control current during that period did not lead to satisfactory answers.

The economic evaluation study was proposed on the rationale that modern methods of mathematical modeling, systems analysis, and operations research could be made to predict the consequences of alternative decisions, if not indeed to reveal optimum economic solutions.

Exploration of the possibility of developing an optimizing model was begun by Mr. Richard Frankel, then an advanced student in water resources engineering, under a one-year predoctoral fellowship from Resources for the Future. Early results indicated that the subject of economic evaluation of water quality might be a fruitful line of research and in 1963 Grant No. WP-00597 was made by the National Institutes of Health in response to a proposal by Professor P. H. McGauhey of the University of California. Subsequently, when the national water resources program was transferred from the Public Health Service to the Department of the Interior, the project was continued under the Federal Water Pollution Control Administration as Grant No. USDI WP-597 until the close of the project in December 1969. During its tenure it produced annual reports on four phases of the study, and a Final Report (herein presented) in which these four reports are summarized and a fifth and final phase of the study presented in detail.

A number of authors are credited with the various reports and the project produced doctoral dissertations in the fields of water resources engineering, economics, and operations research.

The initial phase of the study was an engineering economic model for water quality management. It involved the development of a computer model and its application to a study of the combination of waste water treatment, natural self-purification, and water treatment processes which would involve the least cost to a group of communities in achieving water resource quality goals for a river subject to various water management schemes and multiple beneficial uses. For purpose of the study, the oxygen resource of the stream in terms of dissolved oxygen (DO) was taken as the critical factor governing waste treatment processes. The model, however, was flexible enough to accommodate any combination of water quality criteria and of waste inputs to the river. During the course of phase 1 of the study there was evidence that the normal criteria of average DO concentration of 5 or 6 mg/ℓ might prove inadequate because of the diurnal changes in oxygen concentration and variations in oxygen tension might prove critical and so lead to a whole new concept on which to base the DO criterion of water quality. The second phase of the study was therefore directed to the development and testing of a mathematical model expressing the relationship between the oxygen-demanding fractions of a waste water and the responses of a living stream.

Although the results of the first two phases of the study bore out the rationale of the project, it was evident that with respect to one single criterion or parameter the problem of "indivisibility" or scale factors of treatment processes made for insensitivity of the model in the case of a single stream receiving wastes from but one city and serving another as a source of water supply. That is, the

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model was best suited to a regional network of resources and uses. However, as domestic, industrial, and agricultural wastes may contain various toxic as well as stable compounds which may adversely affect human health or marine ecosystems, DO can no longer be considered the critical standard of water quality. Instead, a multicomponent water quality approach is needed in which limiting concentrations of several important water quality components express the standard.

Phase 3 of the study was designed to reflect a growing emphasis in public policy on "quality of the resource" as contrasted with control of pollutants. It was conducted to develop, and to illustrate by application to an example, a linear programming multicomponent water quality control model capable of minimizing the cost of achieving any given water quality goal when the quantities of various wastes are reduced to levels imposed by presently-known technology. The model made possible an estimate of the minimum cost of achieving quality standards in terms of the maximum allowable quantities of each waste constituent discharged to the receiving water; in this case, one section of San Francisco Bay. Its principal limitation was that instant mixing and dispersion was an implicit assumption. That is, it was assumed that the maximum permissible concentration of a single pollutant resulted from discharging into the estuary the amount of pollutant necessary to produce such a concentration in a dispersed system.

Phase 4 of the study was designed to eliminate to the extent possible the limitation of phase 3 by the development of dispersion models for the optimal allocation of water quality and integration of a dispersion model with the water quality control model of phase 3. The result was a waste treatment model which generates an optimal waste treatment plan for all waste-producing agencies in the study region by minimizing the total waste treatment costs. Finally, a complete model of estuarine water quality management was developed and its use illustrated for Suisun Bay of the San Francisco Bay system.

The final phase of the study develops a multisectional programming analysis for the management of the waste water economy of the San Francisco Bay region, drawing upon a nine-county multisector model of the Bay area economy constructed (by the authors) for the specific purposes of this phase of the study; waste water discharge data and water quality standards for San Francisco Bay; and the steady state linear optimal dispersion model of phase 4. This model included economic and waste water multiplier analyses as well as waste constituent interaction tables and a critical time period analysis. Finally the Bay area waste load data and final demand projections were incorporated into linear programming water quality management models for both untreated effluents and multiphase waste treatment. Thus the final phase of the study presents a method for predicting the discharges which may be permitted in any estuary having known dispersion and advection characteristics. The model was applied under the constraints of the water quality requirements presently imposed upon San Francisco Bay. It also predicts the time when stricter levels of waste treatment must be imposed.

CONCLUSIONS

From the work completed under phases 1 and 2 of the study it was generally concluded that the engineering-economic model has wide applicability to surface water pollution problems. The more than 20 specific conclusions reported include the following:

1. Conventional water treatment plants can handle the pollution load caused by domestic waste disposal at small increases in average annual operating costs.

2. Since large additional downstream treatment costs are incurred only at relatively infrequent intervals, the costs imposed by flows of low probabilities of occurrence are relatively small as compared to the costs imposed by flows occurring more frequently.

3. The costs imposed downstream decrease as the performance of upstream treatment increases, but primary effluent disposal offers little advantage over raw waste disposal in terms of savings to municipal water treatment downstream.

4. Distance is an important factor in imposed costs downstream when little or no treatment is provided upstream but is of minor importance when secondary or higher treatment is provided upstream.

5. When sewage loads are discharged into initially clean streams, the increase in cost to downstream municipal treatment plants is relatively large for the initial pollutional load. Similar increases in pollution loads in already polluted streams result in lower incremental costs to the water treatment plant.

6. The savings to municipal water treatment plants downstream is a direct benefit of improved upstream treatment. The ratio of cost savings downstream to the costs of additional treatment upstream is quite small and varies from negligible to about 0.10. Maximum return per additional investment dollar is realized when secondary treatment is added to primary.

7. The minimum cost conventional treatment alternative to meet coliform standards in the receiving waters is primary waste treatment with heavy chlorination. Average annual costs of maintaining a coliform standard of $\leq$ 2400 MPN/100 mℓ for bathing and recreation uses imposes an added cost to the waste-stream-water system of approximately $31,600 per mgd of domestic sewage discharged for plants of 2.5-mgd capacity and $22,300 per mgd for plants of 10.0-mgd capacity.

8. The costs of maintaining minimum dissolved oxygen levels in the receiving waters for fish and wildlife is very dependent upon stream quality and stream characteristics. Average annual cost estimates based on conventional treatment methods vary between $21,400 and $45,000 per mgd of sewage discharged depending upon the specified dissolved oxygen level, the design flow, and the size of the treatment plant.

9. Variants to conventional treatment operations such as reducing treatment as flow conditions improve, lagooning during low flow periods, or using more operating intensive treatment processes in preference to fixed capital intensive processes, show considerable savings in average annual costs of sewage treatment.

From phase 3 of the report it was evident that a linear water quality control model is an exceedingly useful tool for optimizing the cost of waste treatment. Specifically it was concluded that:

1. Although in the illustrative example the model was applied to secondary treatment processes only and to ten common quality factors, the model could quite as readily be applied to wastes restricted to different quality standards for different quality factors.

2. Only in the case of cities is it necessary to treat the entire waste stream. Industry, by keeping its waste streams separate and applying different treatments as appropriate, has greater latitude in optimizing its costs by use of mathematical models.

3. A considerable reduction in overall cost of achieving imposed standards for the 10 quality factors from the 12 sources examined in the study would result from requiring different levels of treatment by different dischargers of the same waste factor, rather than from imposing the same limit of concentration on each discharger.

In the more sophisticated model utilized in phase 4, the physical system of waste transport and degradation in an estuary was described by a one-dimensional diffusion equation and an estuarine water quality management model developed from a synthesis of dispersion and waste treatment models. From the illustrative examples it was concluded that:

1. The limited boundaries of knowledge about water pollution, waste treatment, and mixing processes in estuaries leave much to be desired in terms of understanding of these processes so that they can be described in precise mathematical terms.

2. A reliable theoretical method is available for most estuarine situations. Additional research is needed to develop a three-dimensional description of the dispersion process along with a method of estimating directional dispersion coefficients.

3. Movement and resulting concentration of conservative substances can be described adequately if a proper description of the dispersive and advective processes is available. However, for nonconservative constituents the accuracy of a model is dependent to a great extent on the reliability of the estimates of the reaction rate constants. Usually these estimates are arrived at by subjective judgments based on the experience of the investigator with the particular environment and waste discharges. There is a need to seek better mathematical descriptions of nonconservative processes, particularly of the biological reactions.

4. The solutions of the water quality control model proposed is sensitive to the water quality standards used. Multicomponent water quality standards are still not available for many estuarine basins. The harmful effects of many constituents by themselves or in conjunction with other constituents on human health and marine ecology are not yet completely understood in quantitative terms. Further research and legislation are needed for establishing proper water quality standards.

5. Quantitative information regarding harmful effects and social costs of pollution and benefits from quality improvement projects are lacking today so that these costs and benefits cannot be included in optimization models. In the report the author has developed deterministic models and considered concentrations averaged over one or more complete tidal cycles. In unsteady state models, only long-term or seasonal variations are considered. Stochastic models may be developed to study variations of water quality during a tidal cycle and effects of random variations of volume of flow in the estuary. There has been some progress in this direction.

Among the most important conclusions from the final phase of the study (Section II of report) are the following:

1. A multisector linear programming water quality model can be formulated and applied to set up optional guidelines for water quality management either to achieve:

    a. minimum costs, or

    b. maximum regional economic development.

2. The use of optimizing techniques for achieving specified water quality levels in receiving waters at minimum cost is a relatively new development; and its extensions indicated in this study are a completely novel development.

3. A pollution multiplier model can be used to forecast the critical time periods under assumption of a growth pattern of the regional economy which is not controlled by any consideration of economic efficiency.

4. The primal-dual relationships determined in the study provide broad guidelines for evaluating the damage costs of effluent discharges and the benefits of maintaining desired water quality levels.

5. An untreated effluent programming model will result in a growth pattern which maximizes the gross regional product while satisfying the required water quality constraints.

6. Treatment of domestic and industrial wastes to a certain extent is economically efficient and permits a higher gross product output for the region while meeting receiving water objectives.

7. The periodic increments to the GRP which result from operating various industries to their upper limit of output are larger for the latter part of a planning horizon.

8. In order to satisfy even the projected lower growth rate of deliveries to final demand, waste treatment processes have to be undertaken immediately in the San Francisco Bay area.

9. The value of fresh water for flushing and dilution purposes can be evaluated within the framework of the technique herein developed.

10. The clearly established pattern, from an evaluation of the study results, is that industrial wastes pose the most difficult problems in maintaining water quality; and the most efficient way of meeting set water quality standards is for industrial dischargers to treat their waste to high levels.

11. The results of the linear programming models show that once it becomes necessary for some level of treatment of an industrial waste to be implemented, complete treatment of total amounts discharged is necessary to meet regional water quality objectives.

APPENDIX

Effluent "Interactions" Tables

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	1	2	3	4	5	6	7
1	0.0000000	0.0000000	0.0000000	.5982747	.1680834	.0407220	.1572144
2	0.0000000	0.0000000	0.0000000	.0172313	.1451006	.0202061	.0780000
3	0.0000000	0.0000000	0.0000000	.0351768	.4700900	.0466437	.1629013
4	0.0000000	0.0000000	0.0000000	7.7819393	.7643755	.0222322	.0788426
5	0.0000000	0.0000000	0.0000000	.0734245	36.5132422	.0675839	.1185608
6	0.0000000	0.0000000	0.0000000	.2068583	1.2290545	1.6755235	.3024895
7	0.0000000	0.0000000	0.0000000	.0253650	.2475552	.0549738	6.5765787
8	0.0000000	0.0000000	0.0000000	.0327008	1.3950085	.0645657	.1074304
9	0.0000000	0.0000000	0.0000000	.0253610	.6064698	.0343349	.0688027
10	0.0000000	0.0000000	0.0000000	.0352755	.8528153	.0506695	.0580845
11	0.0000000	0.0000000	0.0000000	.0435996	.1434202	.0105437	.2092681
12	0.0000000	0.0000000	0.0000000	.0787279	.3278213	.0095947	.0756353
13	0.0000000	0.0000000	0.0000000	.0320824	.1424502	.0092837	.0650924
14	0.0000000	0.0000000	0.0000000	.2336394	.4349646	.0265000	.0739967

	8	9	10	11	12	13	14
1	.0190804	.0116405	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2	.0400336	.0113598	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3	.3414522	.1284023	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
4	.0589200	.0428024	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
5	.0405324	.0248233	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
6	.0717001	.0343538	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
7	.0203146	.0261455	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
8	6.0997129	.0217762	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
9	.0619599	1.4063222	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
10	.0618512	.0513841	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
11	.0225874	.0131309	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
12	.0227691	.0080489	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
13	.0311219	.0122296	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
14	.0343787	.0159675	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

	ROW SUM
1	.9950154
2	.3119313
3	1.1846663
4	8.7491118
5	36.8381670
6	3.5199797
7	6.9509328
8	7.7211946
9	2.2032505
10	1.1100801
11	.4425498
12	.5225973
13	.2922602
14	.8194469

BOD

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             1             2             3             4             5             6             7
 1    24.2934205     0.0000000     0.0000000      .0790174      .0043174      .0233141      .0890968
 2      .0440549     0.0000000     0.0000000      .0022758      .0037271      .0115684      .0442043
 3      .0830530     0.0000000     0.0000000      .0046460      .0120748      .0267044      .0923197
 4     3.0606794     0.0000000     0.0000000     1.0278033      .0196339      .0127283      .0446818
 5      .0593974     0.0000000     0.0000000      .0096976      .9378841      .0386930      .0671909
 6      .1276837     0.0000000     0.0000000      .0273209      .0315697      .9592692      .1714273
 7      .0249049     0.0000000     0.0000000      .0033501      .0063587      .0314736     3.7270891
 8      .0378320     0.0000000     0.0000000      .0043190      .0358324      .0369651      .0608832
 9      .0806859     0.0000000     0.0000000      .0033495      .0155779      .0196574      .0389920
10      .1999436     0.0000000     0.0000000      .0046590      .0219055      .0290093      .0329177
11      .0513880     0.0000000     0.0000000      .0057584      .0036839      .0060365      .1185967
12      .0764920     0.0000000     0.0000000      .0103980      .0084205      .0054932      .0428642
13      .2566844     0.0000000     0.0000000      .0042373      .0036590      .0053151      .0368893
14      .2003647     0.0000000     0.0000000      .0308580      .0111726      .0151717      .0419355

             8             9            10            11            12            13            14
 1      .0001022      .0018660      .0020564     0.0000000     0.0000000     0.0000000     0.0000000
 2      .0002145      .0018210      .0036920     0.0000000     0.0000000     0.0000000     0.0000000
 3      .0018292      .0205836      .0126349     0.0000000     0.0000000     0.0000000     0.0000000
 4      .0003156      .0068615      .0028225     0.0000000     0.0000000     0.0000000     0.0000000
 5      .0002171      .0039793      .0074861     0.0000000     0.0000000     0.0000000     0.0000000
 6      .0003841      .0055071      .0048408     0.0000000     0.0000000     0.0000000     0.0000000
 7      .0001088      .0041913      .0015131     0.0000000     0.0000000     0.0000000     0.0000000
 8      .0326770      .0034908      .0036709     0.0000000     0.0000000     0.0000000     0.0000000
 9      .0003319      .2254410      .0239169     0.0000000     0.0000000     0.0000000     0.0000000
10      .0003313      .0082372      .0712682     0.0000000     0.0000000     0.0000000     0.0000000
11      .0001210      .0021049      .0037497     0.0000000     0.0000000     0.0000000     0.0000000
12      .0001220      .0012903      .0025161     0.0000000     0.0000000     0.0000000     0.0000000
13      .0001667      .0019605      .0024117     0.0000000     0.0000000     0.0000000     0.0000000
14      .0001842      .0025597      .0095612     0.0000000     0.0000000     0.0000000     0.0000000

    ROW SUM
 1    24.4931909
 2      .1115580
 3      .2538455
 4     4.1755264
 5     1.1245457
 6     1.3280027
 7     3.7989895
 8      .2156704
 9      .4079524
10      .3682719
11      .1914392
12      .1475961
13      .3113240
14      .3118076
```

NITROGEN

	1	2	3	4	5	6	7
1	0.0000000	0.0000000	0.0000000	.0037627	.0042583	.0024868	.0010360
2	0.0000000	0.0000000	0.0000000	.0001084	.0036760	.0012340	.0005140
3	0.0000000	0.0000000	0.0000000	.0002212	.0119094	.0028485	.0010735
4	0.0000000	0.0000000	0.0000000	.0489430	.0193649	.0013577	.0005196
5	0.0000000	0.0000000	0.0000000	.0004618	.9250364	.0041273	.0007813
6	0.0000000	0.0000000	0.0000000	.0013010	.0311372	.1023220	.0019933
7	0.0000000	0.0000000	0.0000000	.0001595	.0062716	.0033572	.0433382
8	0.0000000	0.0000000	0.0000000	.0002057	.0353415	.0039429	.0007079
9	0.0000000	0.0000000	0.0000000	.0001595	.0153645	.0020968	.0004534
10	0.0000000	0.0000000	0.0000000	.0002219	.0216055	.0030943	.0003828
11	0.0000000	0.0000000	0.0000000	.0002742	.0036334	.0006439	.0013790
12	0.0000000	0.0000000	0.0000000	.0004951	.0083051	.0005859	.0004984
13	0.0000000	0.0000000	0.0000000	.0002018	.0036089	.0005669	.0004289
14	0.0000000	0.0000000	0.0000000	.0014694	.0110195	.0016183	.0004876

	8	9	10	11	12	13	14
1	0.0000000	0.0000000	.0004113	0.0000000	0.0000000	0.0000000	0.0000000
2	0.0000000	0.0000000	.0007384	0.0000000	0.0000000	0.0000000	0.0000000
3	0.0000000	0.0000000	.0025270	0.0000000	0.0000000	0.0000000	0.0000000
4	0.0000000	0.0000000	.0005645	0.0000000	0.0000000	0.0000000	0.0000000
5	0.0000000	0.0000000	.0014972	0.0000000	0.0000000	0.0000000	0.0000000
6	0.0000000	0.0000000	.0009682	0.0000000	0.0000000	0.0000000	0.0000000
7	0.0000000	0.0000000	.0003026	0.0000000	0.0000000	0.0000000	0.0000000
8	0.0000000	0.0000000	.0007342	0.0000000	0.0000000	0.0000000	0.0000000
9	0.0000000	0.0000000	.0047834	0.0000000	0.0000000	0.0000000	0.0000000
10	0.0000000	0.0000000	.0142536	0.0000000	0.0000000	0.0000000	0.0000000
11	0.0000000	0.0000000	.0007499	0.0000000	0.0000000	0.0000000	0.0000000
12	0.0000000	0.0000000	.0005132	0.0000000	0.0000000	0.0000000	0.0000000
13	0.0000000	0.0000000	.0004823	0.0000000	0.0000000	0.0000000	0.0000000
14	0.0000000	0.0000000	.0019122	0.0000000	0.0000000	0.0000000	0.0000000

	ROW SUM
1	.0119551
2	.0062708
3	.0185796
4	.0707497
5	.9319040
6	.1377217
7	.0534292
8	.0409323
9	.0228575
10	.0395580
11	.0066805
12	.0103878
13	.0052889
14	.0165071

PHOSPHATES

```
            1            2            3            4            5            6            7
 1   0.0000000    0.0000000    0.0000000     .1053566    0.0000000     .0261118     .0378143
 2   0.0000000    0.0000000    0.0000000     .0030345    0.0000000     .0129566     .0187611
 3   0.0000000    0.0000000    0.0000000     .0061947    0.0000000     .0299089     .0391822
 4   0.0000000    0.0000000    0.0000000    1.3704044    0.0000000     .0142557     .0189638
 5   0.0000000    0.0000000    0.0000000     .0129301    0.0000000     .0433362     .0285171
 6   0.0000000    0.0000000    0.0000000     .0364279    0.0000000    1.0743815     .0727569
 7   0.0000000    0.0000000    0.0000000     .0044668    0.0000000     .0352504    1.5818459
 8   0.0000000    0.0000000    0.0000000     .0057586    0.0000000     .0414009     .0258399
 9   0.0000000    0.0000000    0.0000000     .0044661    0.0000000     .0220163     .0165489
10   0.0000000    0.0000000    0.0000000     .0062120    0.0000000     .0324904     .0139709
11   0.0000000    0.0000000    0.0000000     .0076779    0.0000000     .0067608     .0503347
12   0.0000000    0.0000000    0.0000000     .0138640    0.0000000     .0061523     .0181923
13   0.0000000    0.0000000    0.0000000     .0056497    0.0000000     .0059529     .0156565
14   0.0000000    0.0000000    0.0000000     .0411441    0.0000000     .0169924     .0177982

            8            9           10           11           12           13           14
 1    .0000034    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 2    .0000071    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 3    .0000610    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 4    .0000105    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 5    .0000072    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 6    .0000128    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 7    .0000036    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 8    .0010892    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
 9    .0000111    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
10    .0000110    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
11    .0000040    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
12    .0000041    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
13    .0000056    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000
14    .0000061    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000    0.0000000

     ROW SUM
 1    .1692861
 2    .0347593
 3    .0753468
 4   1.4036344
 5    .0847906
 6   1.1835791
 7   1.6215667
 8    .0740887
 9    .0430424
10    .0526843
11    .0647775
12    .0382128
13    .0272647
14    .0759408
```

OIL & GREASE

	1	2	3	4	5	6	7
1	0.0000000	0.0000000	0.0000000	1.3320078	.0264368	2.4731600	.1336452
2	0.0000000	0.0000000	0.0000000	.0383641	.0228219	1.2271708	.0663064
3	0.0000000	0.0000000	0.0000000	.0783181	.0739375	2.8328045	.1384795
4	0.0000000	0.0000000	0.0000000	17.3258270	.1202237	1.3502223	.0670227
5	0.0000000	0.0000000	0.0000000	.1634735	5.7429343	4.1045586	.1007864
6	0.0000000	0.0000000	0.0000000	.4605525	.1933101	101.7592768	.2571410
7	0.0000000	0.0000000	0.0000000	.0564729	.0389364	3.3387159	5.5906336
8	0.0000000	0.0000000	0.0000000	.0728055	.2194120	3.9212564	.0913247
9	0.0000000	0.0000000	0.0000000	.0564642	.0953878	2.0852553	.0584880
10	0.0000000	0.0000000	0.0000000	.0785379	.1341339	3.0773029	.0493766
11	0.0000000	0.0000000	0.0000000	.0970708	.0225576	.6403489	.1778951
12	0.0000000	0.0000000	0.0000000	.1752810	.0515609	.5827153	.0642962
13	0.0000000	0.0000000	0.0000000	.0714287	.0224051	.5638267	.0553339
14	0.0000000	0.0000000	0.0000000	.5201784	.0684128	1.6094189	.0629033

	8	9	10	11	12	13	14
1	.0513467	0.0000000	.0254997	0.0000000	0.0000000	0.0000000	0.0000000
2	.1077332	0.0000000	.0457812	0.0000000	0.0000000	0.0000000	0.0000000
3	.9188724	0.0000000	.1566727	0.0000000	0.0000000	0.0000000	0.0000000
4	.1585578	0.0000000	.0349996	0.0000000	0.0000000	0.0000000	0.0000000
5	.1090755	0.0000000	.0928277	0.0000000	0.0000000	0.0000000	0.0000000
6	.1929500	0.0000000	.0600255	0.0000000	0.0000000	0.0000000	0.0000000
7	.0546680	0.0000000	.0187621	0.0000000	0.0000000	0.0000000	0.0000000
8	16.4147631	0.0000000	.0455192	0.0000000	0.0000000	0.0000000	0.0000000
9	.1667386	0.0000000	.2965694	0.0000000	0.0000000	0.0000000	0.0000000
10	.1664460	0.0000000	.8837259	0.0000000	0.0000000	0.0000000	0.0000000
11	.0607844	0.0000000	.0464966	0.0000000	0.0000000	0.0000000	0.0000000
12	.0612734	0.0000000	.0311995	0.0000000	0.0000000	0.0000000	0.0000000
13	.0837513	0.0000000	.0299056	0.0000000	0.0000000	0.0000000	0.0000000
14	.0925156	0.0000000	.1185583	0.0000000	0.0000000	0.0000000	0.0000000

	ROW SUM
1	4.0420962
2	1.5081776
3	4.1990847
4	19.0568532
5	10.3136559
6	102.9232559
7	9.0991889
8	20.7650809
9	2.7589033
10	4.3895231
11	1.0451534
12	.9663264
13	.8266513
14	2.4719871

TSS

	1	2	3	4	5	6	7
1	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000622	.0108781
2	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000308	.0053970
3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000712	.0112716
4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000339	.0054553
5	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0001032	.0082035
6	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0025581	.0209301
7	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000839	.4550516
8	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000986	.0074334
9	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000524	.0047606
10	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000774	.0040190
11	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000161	.0144798
12	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000146	.0052334
13	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000142	.0045039
14	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0000405	.0051200

	8	9	10	11	12	13	14
1	.0000034	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2	.0000071	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3	.0000610	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
4	.0000105	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
5	.0000072	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
6	.0000128	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
7	.0000036	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
8	.0010892	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
9	.0000111	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
10	.0000110	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
11	.0000040	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
12	.0000041	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
13	.0000056	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
14	.0000061	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

	ROW SUM
1	.0109437
2	.0054350
3	.0114038
4	.0054998
5	.0083140
6	.0235009
7	.4551391
8	.0086212
9	.0048241
10	.0041074
11	.0145000
12	.0052521
13	.0045237
14	.0051666

PHENOL

	1	2	3	4	5	6	7
1	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0360591	.0018130
2	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0178924	.0008995
3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0413028	.0018786
4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0196865	.0009092
5	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0598452	.0013673
6	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	1.4836697	.0034883
7	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0486791	.0758419
8	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0571727	.0012389
9	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0304034	.0007934
10	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0448677	.0006698
11	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0093364	.0024133
12	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0084961	.0008722
13	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0082207	.0007507
14	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	.0234656	.0008533

	8	9	10	11	12	13	14
1	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
2	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
4	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
5	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
6	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
7	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
8	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
9	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
10	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
11	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
12	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
13	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
14	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

	ROW SUM
1	.0378722
2	.0187919
3	.0431814
4	.0205957
5	.0612125
6	1.4871580
7	.1245210
8	.0584116
9	.0311969
10	.0455375
11	.0117497
12	.0093683
13	.0089714
14	.0243190

GROSS HEAVY METALS

```
            1             2             3             4             5             6             7
 1    84.4866177     0.0000000     0.0000000      .6829362      .5245952     1.0401198      .4913274
 2      .1532122     0.0000000     0.0000000      .0196697      .4528649      .5161027      .2437660
 3      .2888381     0.0000000     0.0000000      .0401546     1.4671705     1.1913731      .5091000
 4    10.6442999     0.0000000     0.0000000     8.8831571     2.3856475      .5678537      .2463992
 5      .2065699     0.0000000     0.0000000      .0838148   113.9593449     1.7262259      .3705268
 6      .4440528     0.0000000     0.0000000      .2361307     3.8359302    42.7961966      .9453419
 7      .0866131     0.0000000     0.0000000      .0289543      .7726300     1.4041407    20.5531626
 8      .1315706     0.0000000     0.0000000      .0373282     4.3538795     1.6491357      .3357423
 9      .2806058     0.0000000     0.0000000      .0289499     1.8928173      .8769814      .2150227
10      .6953553     0.0000000     0.0000000      .0402673     2.6616720     1.2942000      .1815259
11      .1787153     0.0000000     0.0000000      .0497693      .4476203      .2693071      .6540058
12      .2660205     0.0000000     0.0000000      .0898687     1.0231440      .2450686      .2363759
13      .8926860     0.0000000     0.0000000      .0366223      .4445929      .2371247      .2034271
14      .6968198     0.0000000     0.0000000      .2667016     1.3575426      .6768622      .2312548

            8             9            10            11            12            13            14
 1      .0775481      .0963233      .0415399     0.0000000     0.0000000     0.0000000     0.0000000
 2      .1627078      .0940005      .0745791     0.0000000     0.0000000     0.0000000     0.0000000
 3     1.3877595     1.0625042      .2552249     0.0000000     0.0000000     0.0000000     0.0000000
 4      .2394676      .3541816      .0570155     0.0000000     0.0000000     0.0000000     0.0000000
 5      .1647351      .2054081      .1512192     0.0000000     0.0000000     0.0000000     0.0000000
 6      .2914096      .2842711      .0977835     0.0000000     0.0000000     0.0000000     0.0000000
 7      .0825643      .2163493      .0305641     0.0000000     0.0000000     0.0000000     0.0000000
 8    24.7909760      .1801941      .0741522     0.0000000     0.0000000     0.0000000     0.0000000
 9      .2518229    11.6370475      .4831211     0.0000000     0.0000000     0.0000000     0.0000000
10      .2513810      .4251940     1.4396180     0.0000000     0.0000000     0.0000000     0.0000000
11      .0918018      .1086554      .0757445     0.0000000     0.0000000     0.0000000     0.0000000
12      .0925403      .0666030      .0508250     0.0000000     0.0000000     0.0000000     0.0000000
13      .1264883      .1011979      .0487172     0.0000000     0.0000000     0.0000000     0.0000000
14      .1397249      .1321282      .1931352     0.0000000     0.0000000     0.0000000     0.0000000

       ROW SUM
 1    87.4410076
 2     1.7169030
 3     6.2021250
 4    23.3780221
 5   116.8678447
 6    48.9311164
 7    23.1749786
 8    31.5529788
 9    15.6663687
10     6.9892135
11     1.8756191
12     2.0704459
13     2.0908566
14     3.6941694
```

TOTAL EFFLUENT

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10 Author(s)
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JONA BARGUR
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27 Abstract

The tendency to set quality of the water resource rather than quality of discharges as the objective of environmental control makes it necessary to develop some relationship between concentration of individual pollutants in the resource and in the discharge in terms of characteristics of the receiving estuary. Moreover, the growing percentage of the water resource which is degraded in quality through beneficial use together with the increasing investment necessary to restore water quality, makes it important to minimize the cost of achieving water quality objectives. The study makes use of modern mathematical models, programming techniques, and input-output analysis to optimize quality control systems; and illustrates the use of the models by examples drawn from San Francisco Bay data and quality requirements.

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